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Office of Environment
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Possibility of Hearing Loss from Exposure to Interior Aircraft Noise

Karl S. Pearsons
John F. Wilby

November 1981

Final Report

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16. Abstract
This report reviews criteria for hearing damage developed by the Committee on Hearing, Bioacoustics and Biomechanics (CHABA) of the National Academy of Science. It presents noise levels occurring in narrow and wide body commercial aircraft, business jet aircraft and short takeoff and landing (STOL) aircraft. It presents estimates of time exposure for pilots and crews based on FAA permitted flight times. It also provides estimations of possible hearing damage resulting from different exposures to interior noise of various aircraft types.

17. Key Words
Hearing Damage, CHABA, flight time exposure, aircraft interior noise

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FIGURES (Continued)

POSSIBILITY OF HEARING LOSS FROM EXPOSURE TO INTERIOR AIRCRAFT NOISE

I. INTRODUCTION

Pilots and crew of jet aircraft are exposed to noise during flight and some concern has been expressed that the exposure might have a detrimental effect on the hearing of crew members, including cabin attendants. At the request of the Federal Aviation Administration, a research project has been undertaken to assemble noise levels and exposure times to which pilots and crew of various types of jet aircraft may be exposed to investigate the possibility of any possible hearing damage. Further, damage risk criteria have been assembled and organized to evaluate any potential hearing damage from exposure to jet aircraft interior noise.

Section II of this report reviews criteria for hearing damage developed by the Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) of the National Academy of Science, and explores extrapolations of the criteria to assess greater than eight hour noise exposure times. As a starting point to assess the effects of aircraft interior noise, it was FAA's intent to develop new damage risk criteria (DRC) as appropriate using recent information on hearing damage from non-8-hour-per-day noise. The new DRC was to be similar to, and account for, the same assumptions as the original CHABA criteria. Section III presents levels occurring in narrow body and wide body commercial aircraft, business jet aircraft and short takeoff and landing (STOL) aircraft at crew and passenger locations for climb, cruise and descent operations. Section IV presents estimates of the time exposure for pilots and crews for various types of aircraft based on FAA utilization estimates and

maximum flight times permitted by FAA for safety purposes. Section V combines the results of Sections II, III and IV to provide estimations of possible hearing damage resulting from different exposures to interior noise of various aircraft types. Section VI provides conclusions resulting from the entire investigation highlighting the major findings.

II. HEARING DAMAGE RISK CRITERIA

Studies have been performed to determine how much hearing loss is experienced after exposure to different amounts of noise. From this information, limits can be established to prevent excessive damage to the hearing mechanism. The Committee on Hearing Bioacoustics and Biomechanics (CHABA) have summarized studies (CHABA 1965) related to the effect of noise on hearing. The results indicate limits of octave or one-third octave bands of noise necessary to protect people's hearing for various durations of up to eight hours. The values assume a daily exposure for 10 years or more.

The basic damage risk criterion set forth in the original CHABA document states that "a sound environment will be deemed acceptable if it produces on the average a permanent noise induced hearing loss in people after ten years or more of near daily exposure of no more than 10 dB at 1000 Hz or below, no more than 15 dB at 2000 Hz, or no more than 20 dB at 3000 Hz or above". Thus, using this definition, and the assumption that the median and the mean are similar, 50% of the people would have losses greater than these amounts, and 50% of the people would have less.

The development of the damage risk criterion was further based on three postulates. Simply stated, they are:

1) Temporary Threshold Shift (TTS) is a constant measure of the effects of a single day's

exposure to noise;

2) All exposures that produce a given TTS_2 (a TTS Measured two minutes after cessation of noise exposure) will be equally hazardous; and,

3) TTS_2 is approximately equal to the noise induced permanent threshold shift (NIPTS) after ten years.

The third postulate, of course, is the strongest, and was even at that time open to question. Final limits for both broad-band noise and pure tones are given as damage risk contours in Figures 1 and 2.

These contours provide the maximum octave or one-third octave band levels for specified daily amounts of time. Figures 1 and 2 indicate the maximum level which may be tolerated for a specified amount of time, or conversely, the maximum amount of time an individual may be exposed at a specified sound level. Octave or one-third octave band data may be plotted on these figures to determine which particular one-third octave band controls or limits the noise exposure for a specific environment. Noises with fluctuating levels may also be evaluated using these figures provided that (a) the noise does not remain at a single level more than two minutes, and (b) the level never drops below "480 minute" curves shown in the figures. The effective level of such a varying noise is equal to the weighted average sound pressure level of the noise over the exposure.

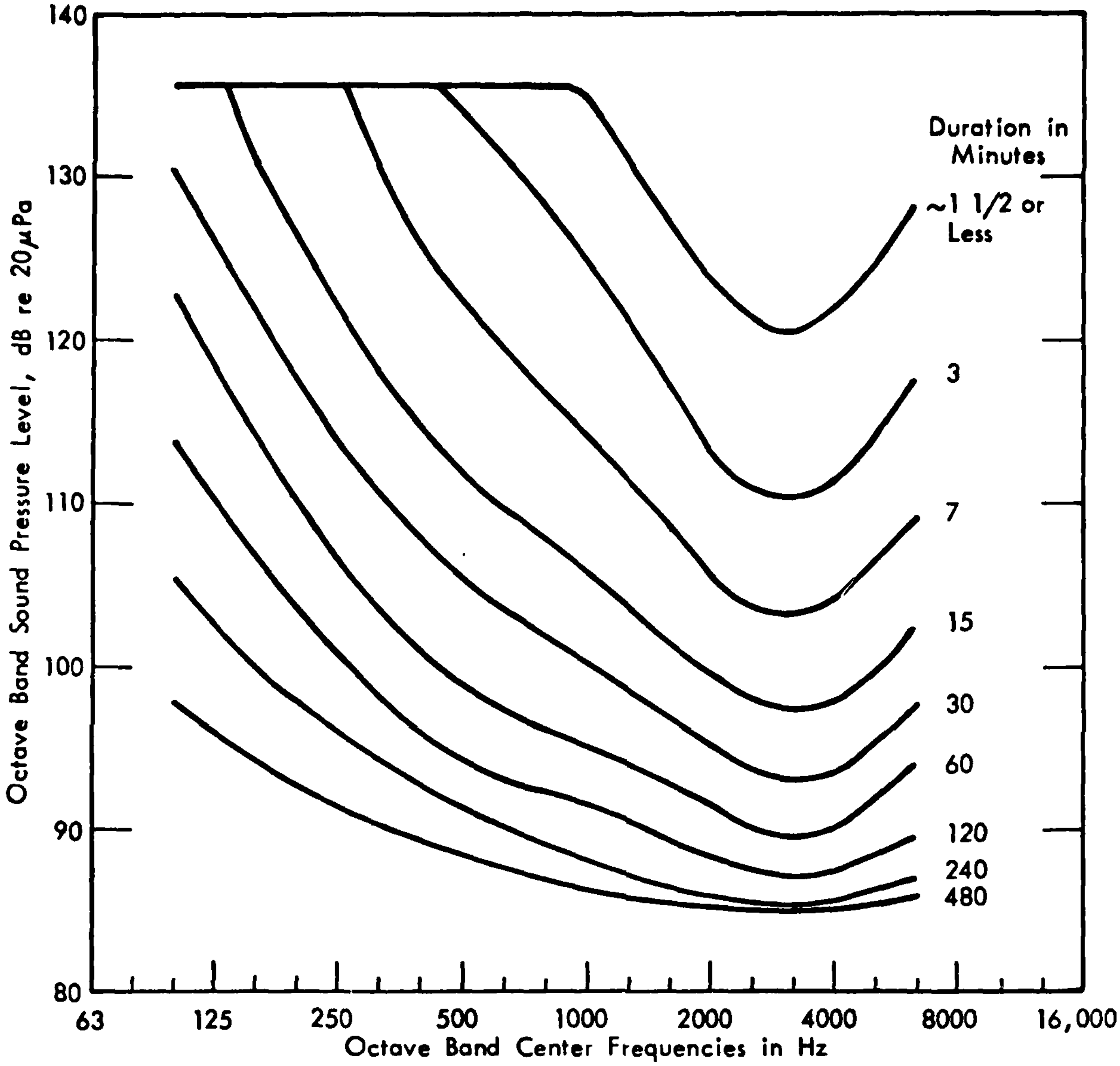


FIGURE 1. DAMAGE RISK CONTOURS FOR ONE EXPOSURE PER DAY TO OCTAVE BANDS OF NOISE

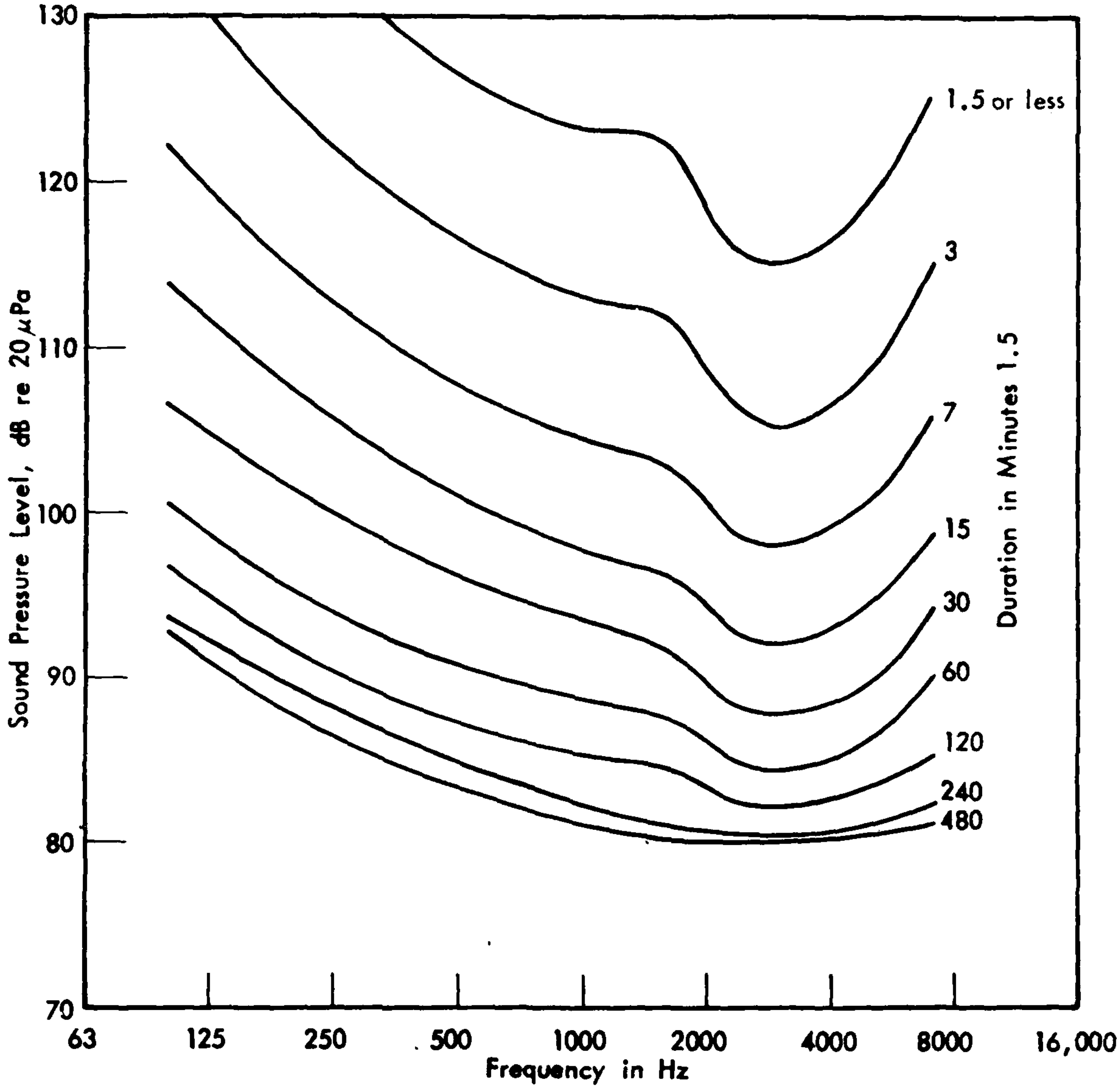


FIGURE 2. DAMAGE RISK CONTOURS FOR ONE EXPOSURE PER DAY TO PURE TONES

For sounds lasting longer than two minutes, followed by quiet periods, a different technique is employed. For these cases, graphs are provided in the original reference (CHABA 1965) which indicate the necessary amount of quiet time (levels below the 480 minute contour) which must follow the specified noise bursts in order to provide a safe daily exposure pattern which will not exceed the criteria given above. The graphs are not presented here since they do not reflect exposure patterns found in the majority of the aircraft interiors. However, for special situations they may be of some importance.

Aircraft crew schedules do not conform to a uniform daily schedule. Thus, some schedules produce exposures of 12 or more hours in duration followed by a day of rest without aircraft noise exposure at all. Further details on exposure times will be discussed in sections to follow. However, some extrapolation of the damage risk contour seemed appropriate to encompass longer exposure times than those presented for the original damage risk contours. Simple extrapolation was employed to provide the damage risk contour for sixteen hours as shown in Figure 3. Actually, the difference between eight hours and sixteen hours is not great suggesting that the contours are asymptoting toward some minimum value. A revised set of contours which include the sixteen hour limit is shown in Figure 4.

III. AIRPLANE INTERIOR NOISE

A. Background

Noise levels inside jet powered aircraft are determined by a variety of factors including airplane speed, exterior flow

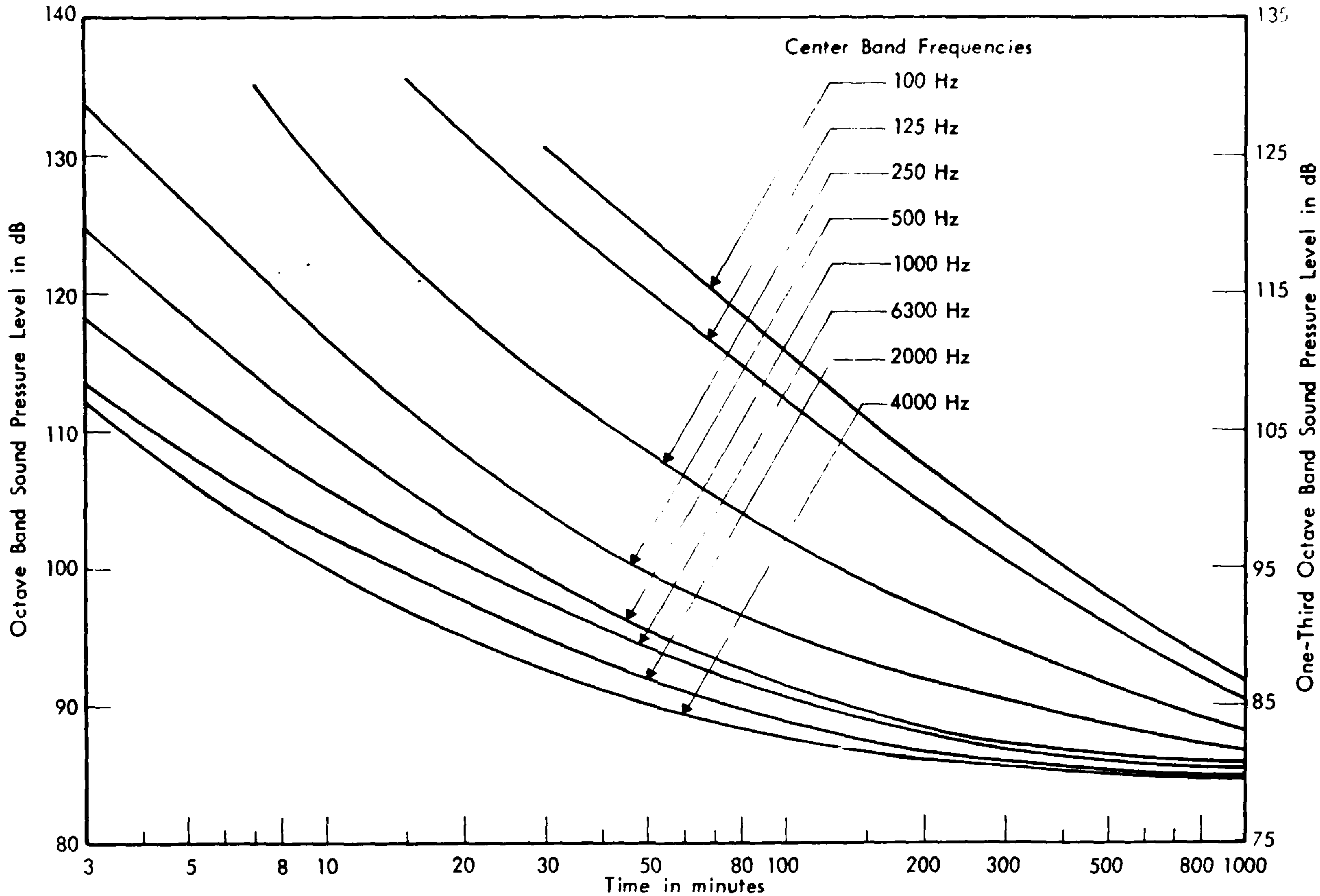


FIGURE 3. DAMAGE RISK CONTOURS FOR ONE EXPOSURE PER DAY TO CERTAIN OCTAVE BAND (LEFT HAND ORDINATE) AND CERTAIN ONE-THIRD OCTAVE BAND (RIGHT HAND ORDINATE) NOISE. THIS GRAPH CAN BE APPLIED TO INDIVIDUAL BAND LEVELS PRESENT IN BROADBAND NOISE.

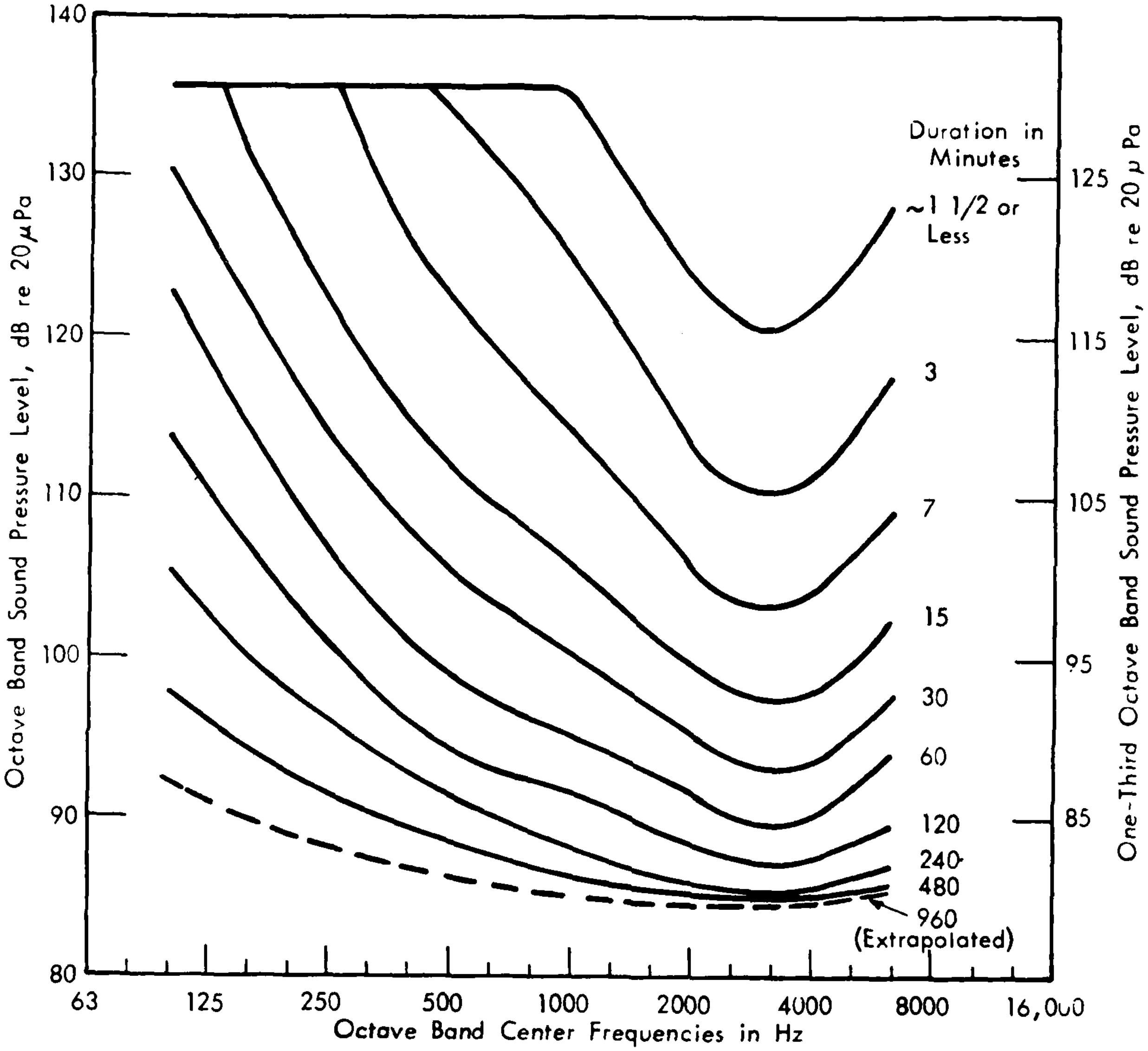


FIGURE 4. DAMAGE RISK CONTOURS FOR ONE EXPOSURE PER DAY TO OCTAVE OR ONE THIRD OCTAVE BANDS OF NOISE

conditions, engine location and mounting, fuselage structure, interior air conditioning, and cabin sidewall treatments and furnishings. Thus it is to be expected that noise levels will vary along the length of an airplane cabin, and from airplane type to airplane type. Aircraft with engines mounted on the rear of the fuselage (eg DC-9) are more likely to have structure borne noise components at the rear of the cabin (Van Dyke et al, 1967) whereas aircraft with wing mounted engines (eg Boeing 737) may have jet noise contributions (Wilby et al., 1972). In the cockpit and forward part of the cabin of commercial transports, engine noise is probably negligible, and the sound levels are usually determined by external flow conditions. Noise control treatment is present in the passenger cabin but, because of the presence of equipment, the amount of treatment is often less in the cockpit.

Interior noise levels will change with time during any given flight. Since the majority of the time of a flight is associated with cruise conditions, noise levels associated with cruise are of main interest. However, some consideration has to be given to other flight regimes such as climb and descent. Takeoff and landing occur for such short portions of the flight that the effects on the total noise exposure can be neglected. For example the duration of a typical takeoff roll for a commercial transport is about 35 seconds, with takeoff thrust held for about one minute, and the duration of thrust-reverse operation on landing is no more than about 5 seconds. Enroute climb and descent as distinct from initial climb, final descent, and approach, do represent significant portions of the flight time and, thus, have to be considered in the exposure evaluation. Typical time histories for cabin noise levels in commercial transports (EPA, 1971) are reproduced here in Figure 5.

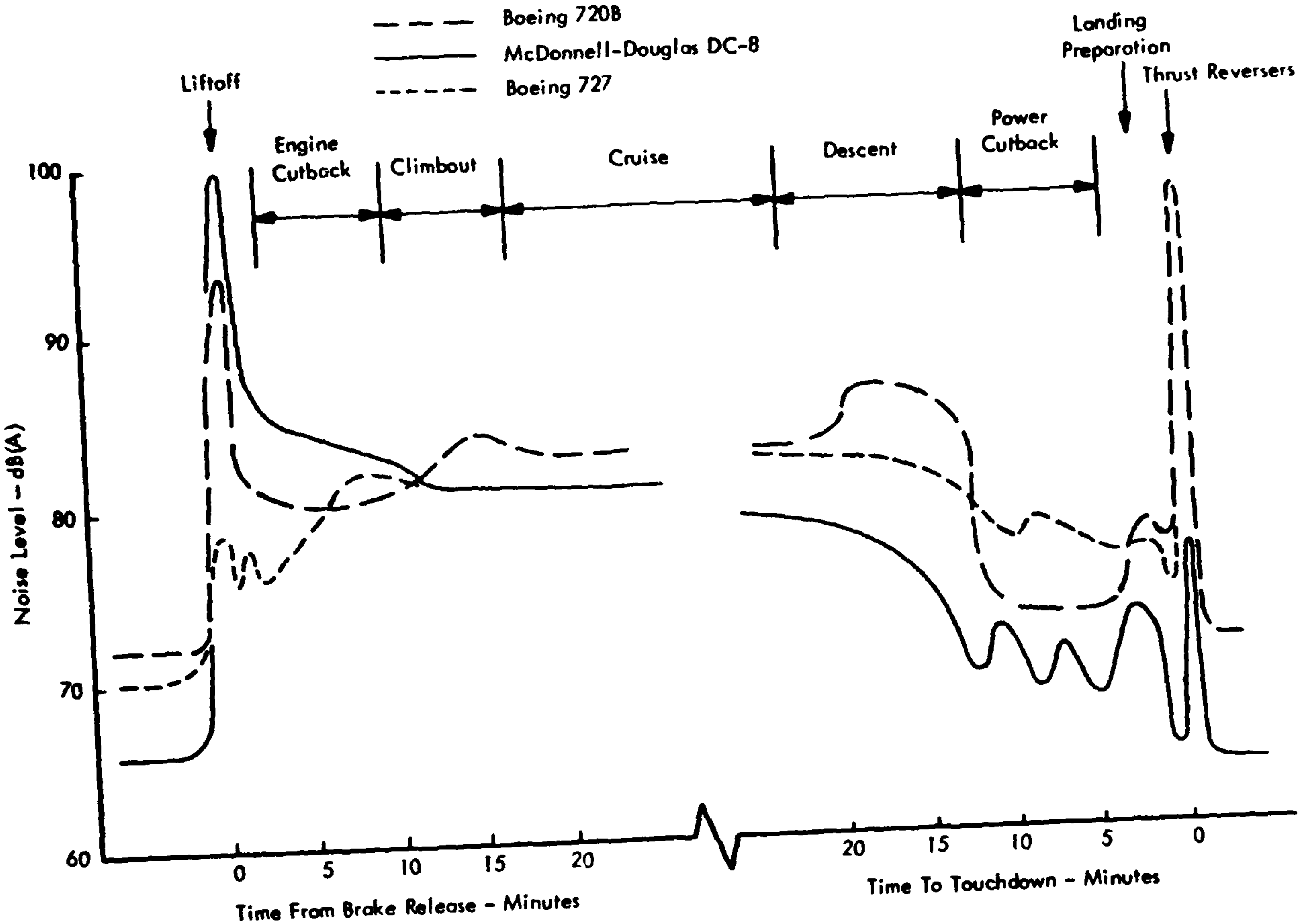


FIGURE 5. TIME HISTORIES OF TYPICAL CABIN NOISE LEVELS
[EPA, 1971]

B. Noise Measurements

Airplane interior noise levels have been measured in jet powered conventional take-off and landing (CTOL) and short take-off and landing (STOL) aircraft by a number of investigators (indicated by an asterisk in the list of references) under various conditions. These measurements are supplemented by unpublished data. In some cases the airplanes were in fully furnished conditions associated with commercial or business operation, but in others there was little or no interior noise control treatment, the aircraft being in either military or experimental configurations. Thus adjustments have to be made to the results to make allowance for acoustic treatment. These adjustments can be made on the basis of empirical noise transmission data and analytical procedures, such as those applied to STOL aircraft as described in Appendix A. In some cases measurements were made in aircraft which had additional noise control treatment (Anon, 1977).

Data were obtained for various flight conditions but it is not practical to make interior noise measurements for all possible flight conditions. Thus some adjustments have to be made to the data to make them representative of all cruise conditions likely to be encountered in service. In order to make these adjustments it is necessary to have some extrapolation procedure. Details of this procedure are given in Appendix A.

C. Commercial Transports

Jet-powered commercial transports have been in airline service since 1959. Variants of two of the early designs, the

Boeing 707 and McDonnell Douglas DC-8, are still in scheduled passenger service in the U.S.A. Others, such as the Boeing 720 and Convair 880/990, are no longer in scheduled service but data available for these aircraft are included in the analysis since the aircraft operating conditions were similar to those of present-day aircraft. Other narrow body aircraft included in the study are the Boeing 707, 727, and 737, McDonnell Douglas DC-8 and DC-9, and British Aerospace BAC-111, for a total of eight different types with two, three, or four engines. In the case of wide body aircraft, data were obtained for the Lockheed L-1011, McDonnell Douglas DC-10 and Boeing 747. Data were obtained for a range of flight conditions varying from flight durations of less than 30 minutes at altitudes below 4600m (15,000 feet) to typical long range cruise conditions at altitudes of 9,2000m (30,000 feet) and above.

A total of 95 data points were obtained for narrow body cabin noise levels and 64 points for wide body airplanes. The distributions of measurement locations along the cabin were fairly uniform as shown in Figure 6. For the narrow body aircraft 38% of the data points were in the forward third of the cabin, 32% in the mid third and 30% in the rear third. The corresponding distribution for wide body aircraft was 30%, 36% and 34%. Cockpit noise measurements include 19 data points for narrow body and 5 points for wide body aircraft.

The variation of interior noise level with flight conditions was evaluated using the relationship $p \propto \rho^2 V^{4.5}$, as given in Appendix A. A cruise condition having a flight velocity of 495 knots at an altitude of 9,200 m (30,000 feet) was selected as a reference, and it was found that the measurement

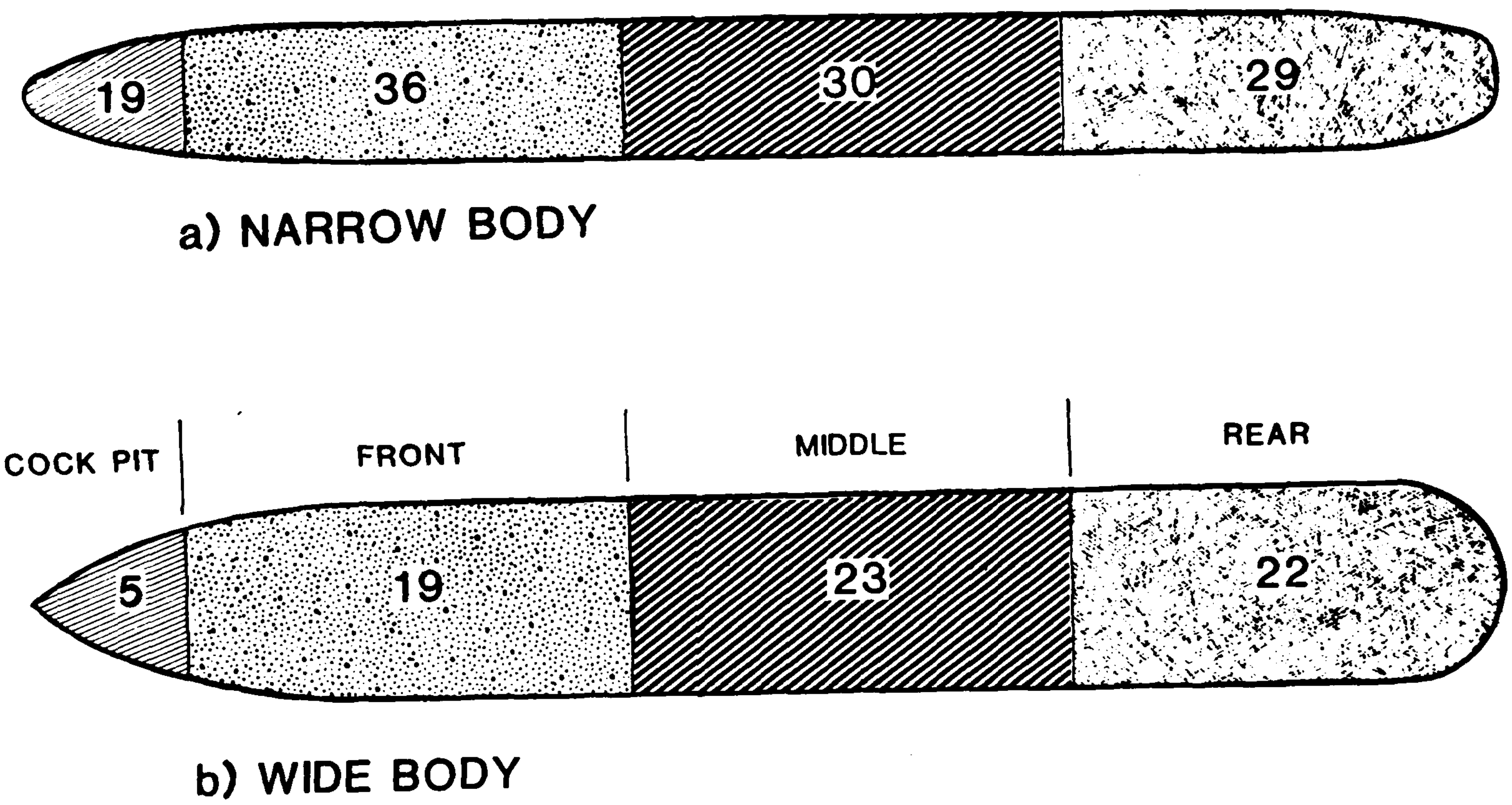


FIGURE 6. NUMBERS OF ACOUSTICAL MEASUREMENTS FOR WIDE-BODY AND NARROW-BODY COMMERCIAL JET AIRCRAFT

flight conditions during noise measurement resulted in a predicted variation of ±2.5 dB about the noise for the reference condition. Next, typical cruise conditions for the airplanes of interest were obtained (Janes, 1971-1980), the predicted variations in sound level for typical cruise conditions relative to those for the reference condition were again ±2.5 dB. Thus it was deduced that the measured sound levels were representative of those likely to be encountered in service.

Cabin and cockpit interior sound levels for jet-powered commercial transports in cruise are presented in Figures 7 and 8, respectively, for narrow body aircraft, and Figures 9 and 10 for wide body aircraft. The sound levels are presented in terms of average octave band levels and associated standard deviations. The statistical calculations involved in obtaining mean values and standard deviations were made using sound pressure levels (decibel values) since it was considered to be sufficiently accurate for present purposes. Data from early measurements in DC-9 aircraft (e.g. Stone 1969) had exceptionally high noise levels in the octave bands centered at 125 and 250 Hz. These measurements have been excluded from the analysis because such levels, generated by structure-borne transmission of engine noise, were later reduced by noise control procedures (Van Dyke et al., 1967).

A comparison of the spectra in Figures 7 and 9 with those in Figures 8 and 10 shows the characteristic difference between spectra shapes for cabin and cockpit sound pressure levels. The cabin has highest sound levels at low frequencies, and decreasing levels at higher frequencies. In con-

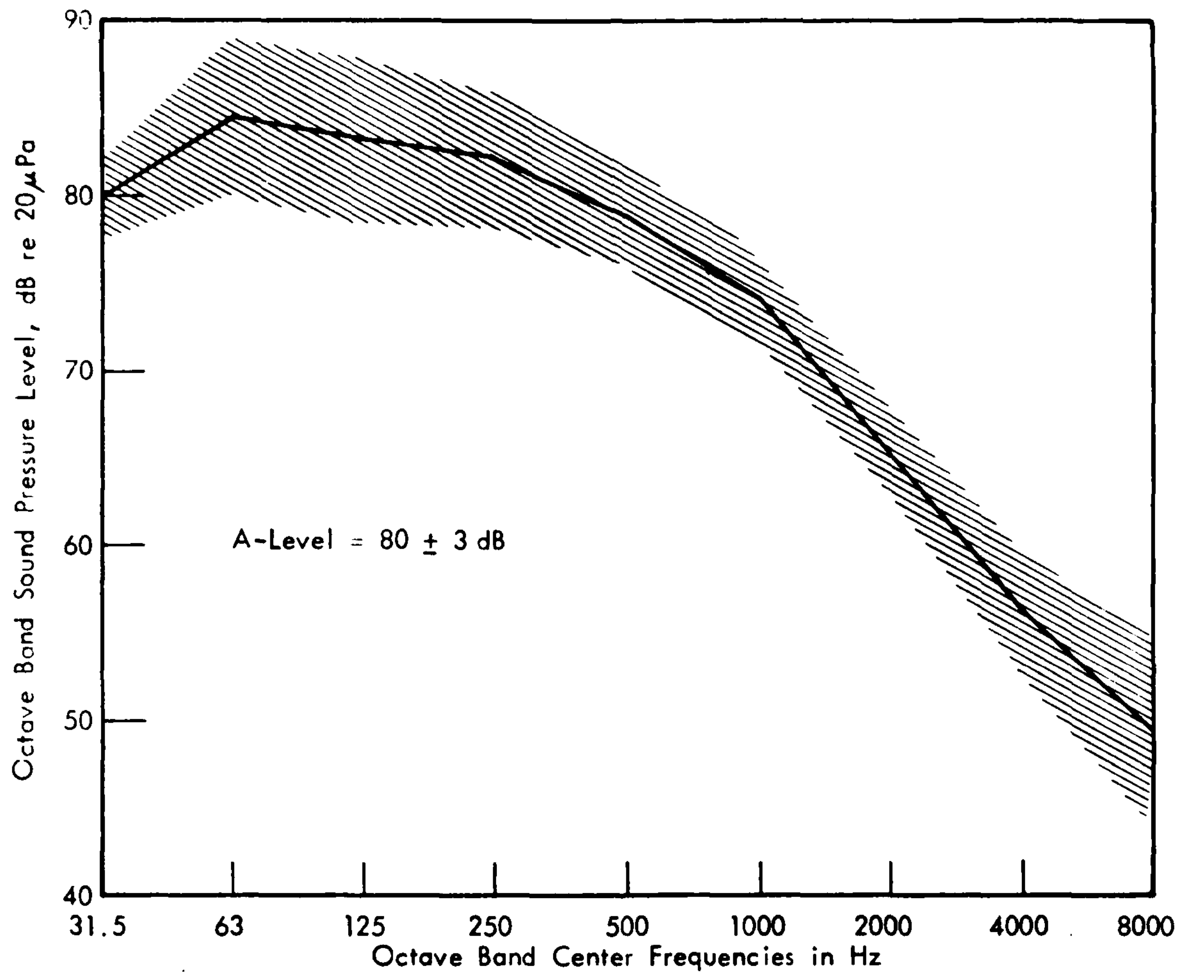


FIGURE 7. CABIN NOISE LEVELS FOR NARROW BODY AIRCRAFT DURING CRUISE (MEAN ± ONE STANDARD DEVIATION)

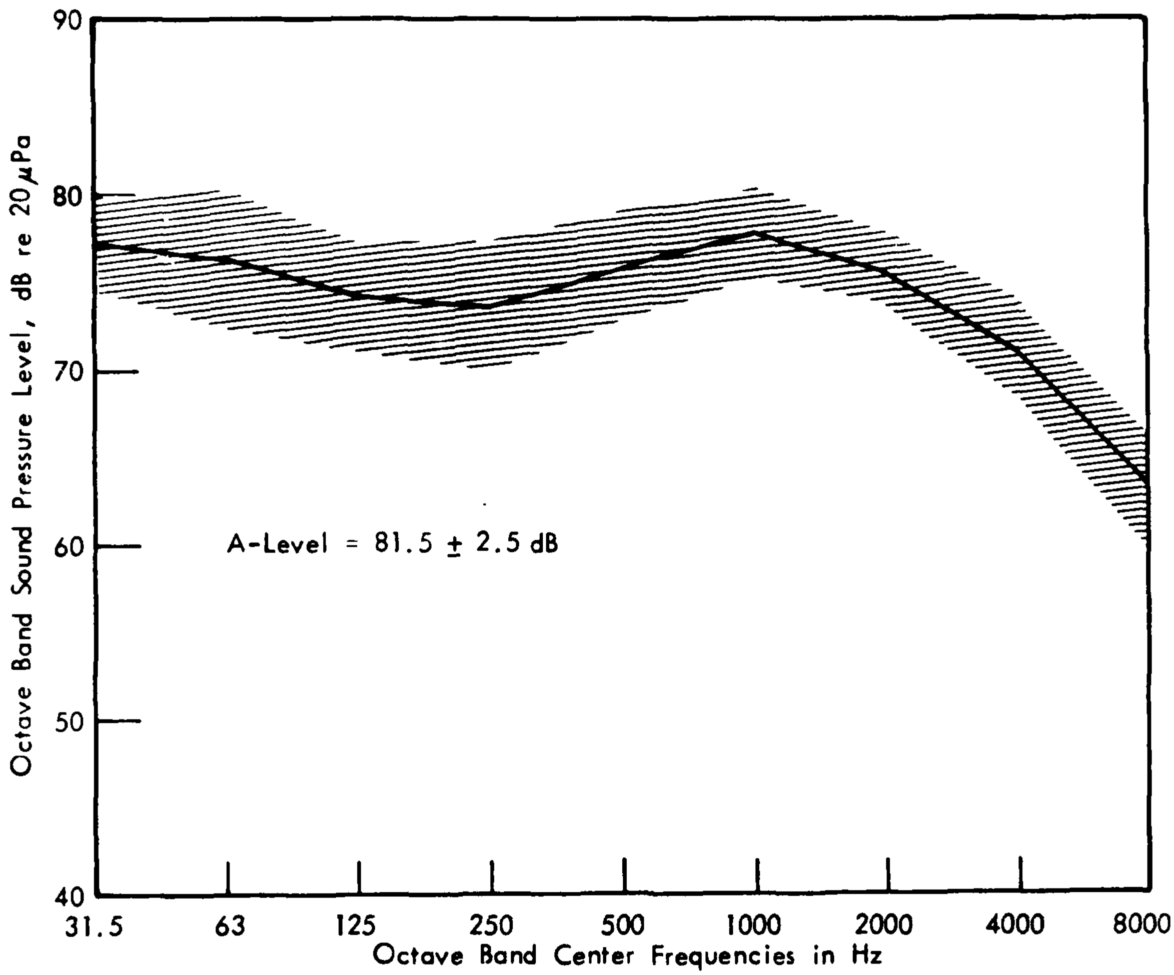


FIGURE 8. COCKPIT NOISE LEVELS FOR NARROW BODY AIRCRAFT DURING CRUISE (MEAN ± ONE STANDARD DEVIATION)

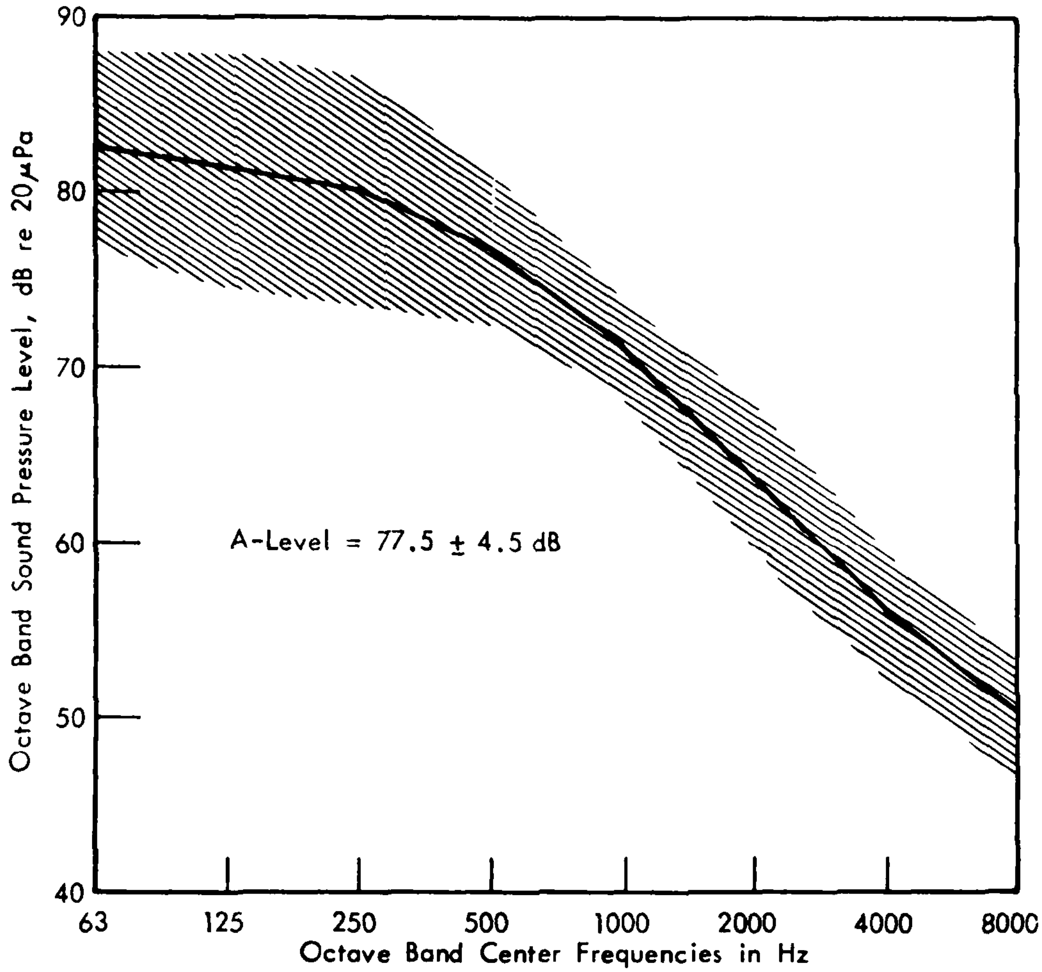


FIGURE 9. CABIN NOISE LEVELS FOR WIDE BODY AIRCRAFT DURING CRUISE (MEAN ± ONE STANDARD DEVIATION)

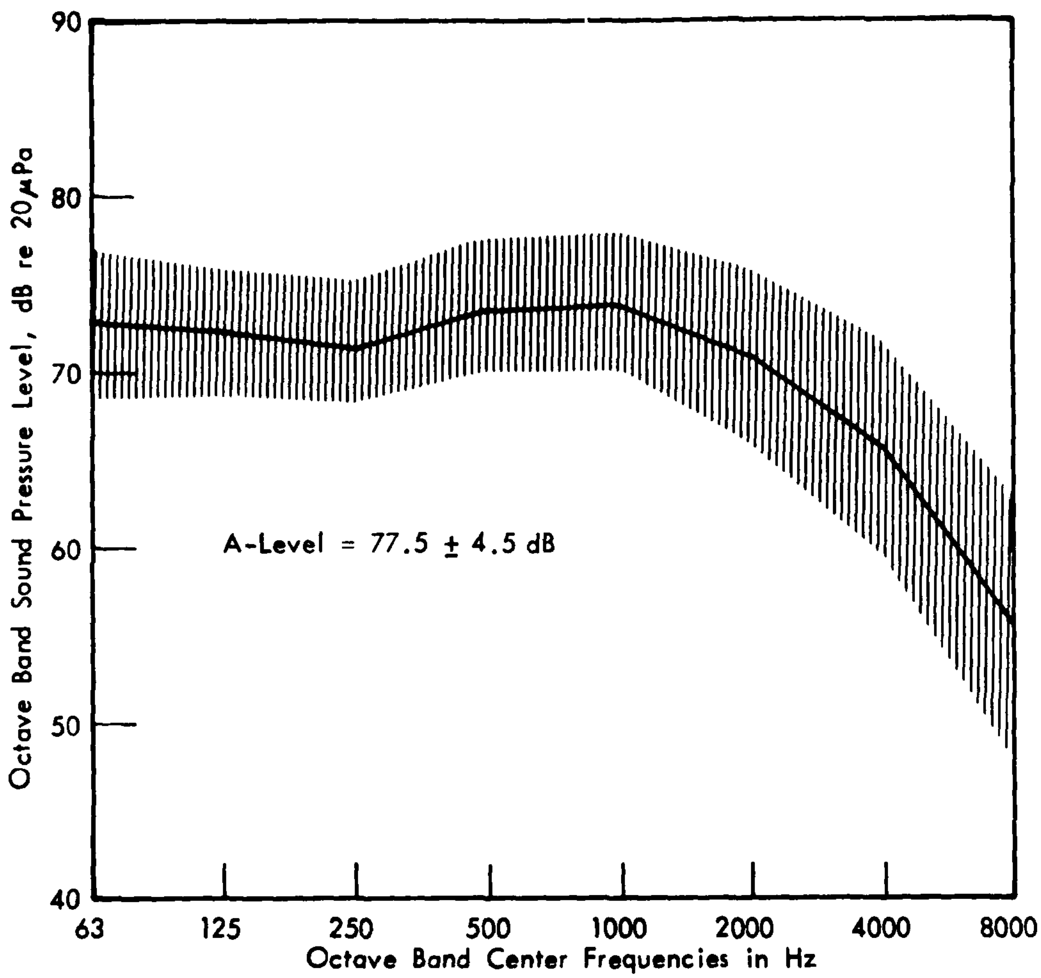


FIGURE 10. COCKPIT NOISE LEVELS FOR WIDE BODY AIRCRAFT DURING CRUISE (MEAN ± ONE STANDARD DEVIATION)

trast, cockpit noise levels at low frequencies are somewhat lower than in the cabin but, at high frequencies, the levels are significantly higher than in the cabin.

In general, enroute climb and descent conditions (engine thrust and aircraft speed) are similar to those for cruise. Thus, it is reasonable to assume that the interior noise levels will also be similar. It might be argued that during climb, engine thrust will be slightly higher and flight speed slightly lower than in cruise, with the result that low frequency sound levels will be higher and high frequency levels lower. The converse might be true for descent. Available data, however, indicate that low frequency sound levels are, on the average, the same for enroute climb, cruise and descent. Also, average high frequency sound levels are lower during climb and descent than during cruise, with the lowest levels occurring during climb. Spectra for cabin sound levels in narrow body aircraft during climb and descent are shown in Figure 11. An exception to the general trend is observed in the cockpit during high-speed descent. For high speed descent average measured high frequency sound levels in the cockpit are 3 to 4 dB higher than the cruise average values as shown in Figure 12. Although the data presented in Figures 11 and 12 refer specifically to narrow body aircraft, similar trends are anticipated for wide body aircraft.

D. Business Jet Aircraft

1. Measurement Conditions

The range of typical operating conditions for business jet aircraft is considerably greater than that for subsonic

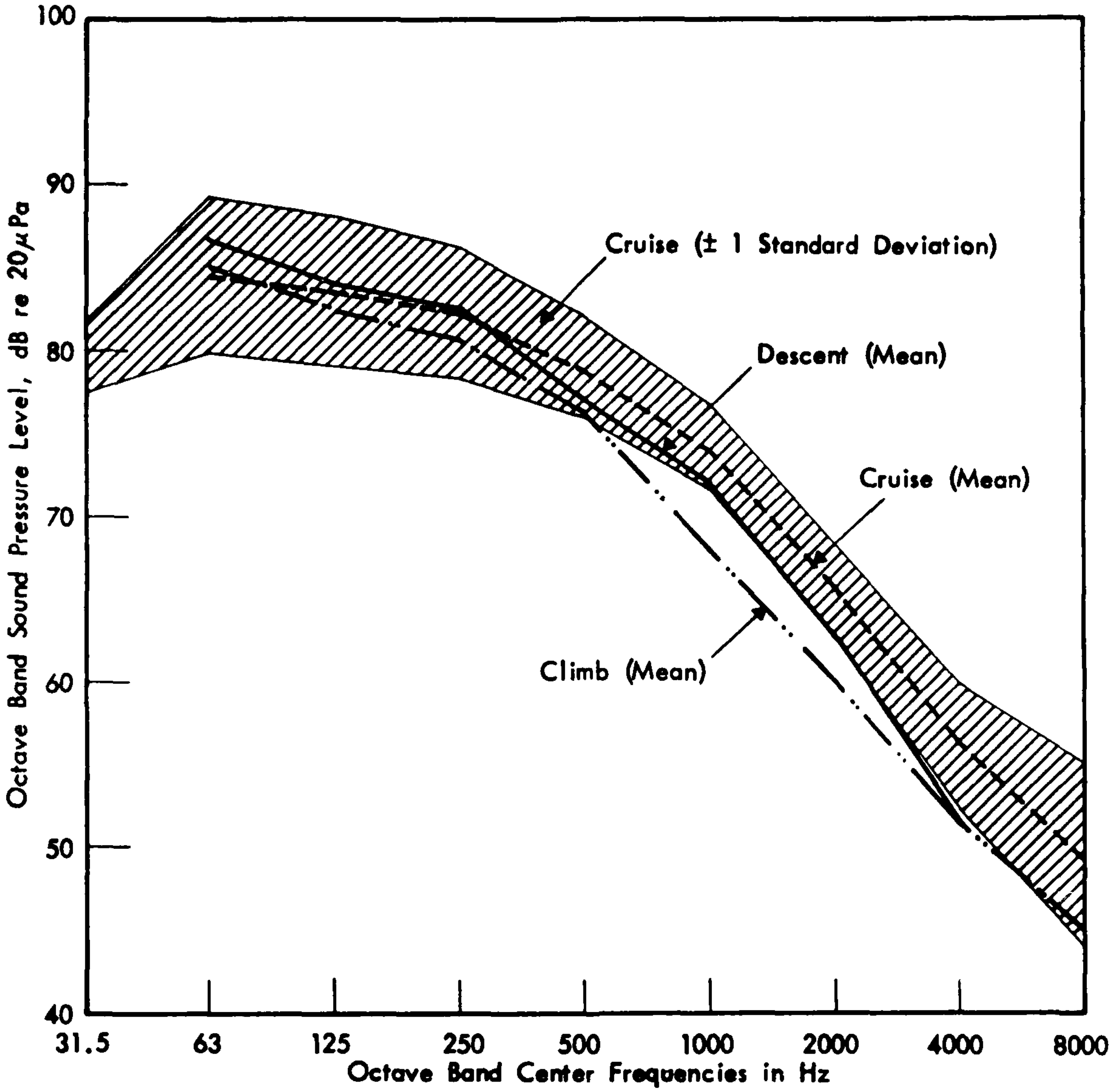


FIGURE 11. CABIN NOISE LEVELS FOR NARROW BODY AIRCRAFT DURING CLIMB AND DESCENT

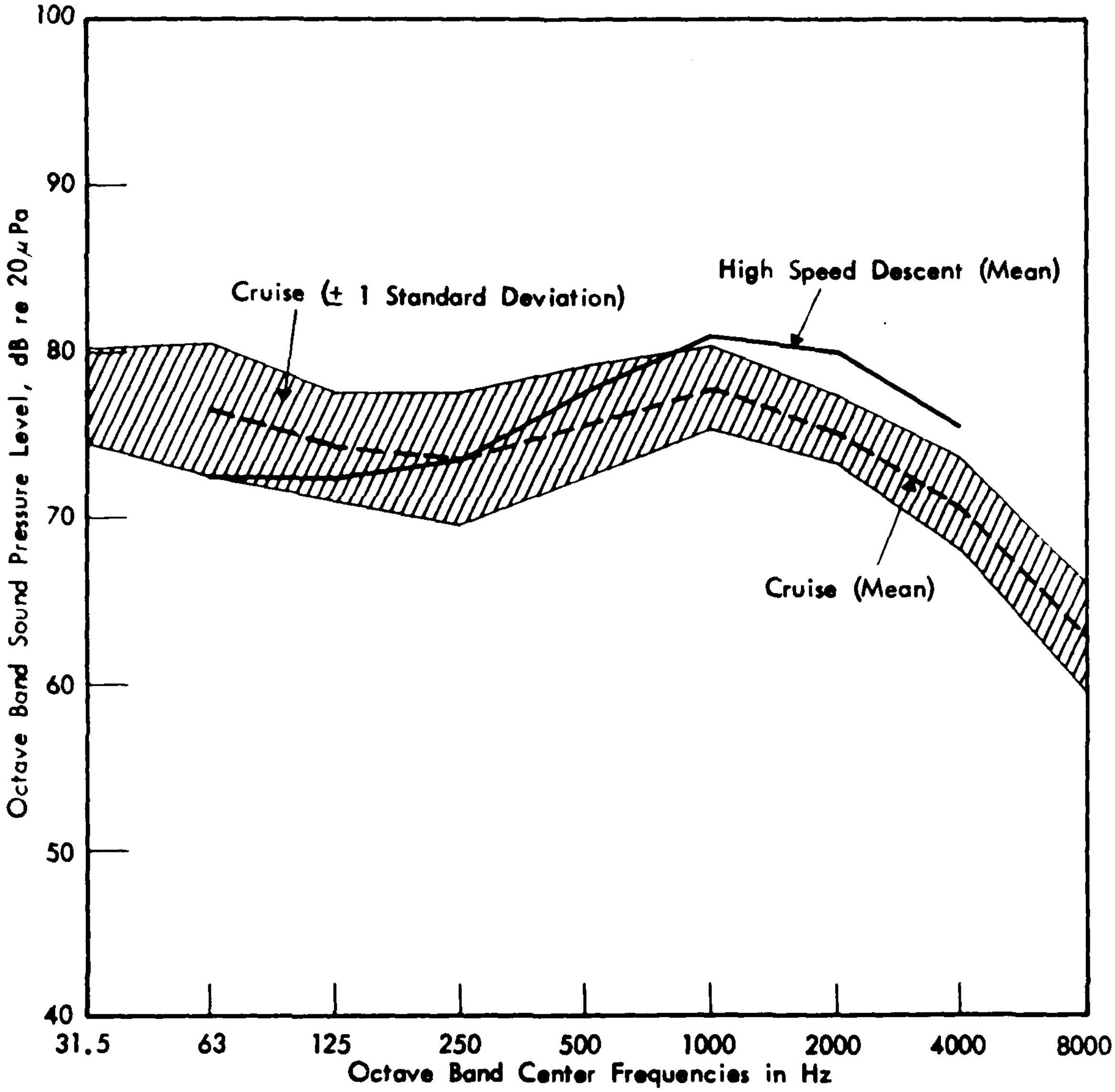


FIGURE 12. COCKPIT NOISE LEVELS FOR NARROW BODY AIRCRAFT DURING HIGH SPEED DESCENT

commercial jet transports. Consequently, it is unlikely that available interior noise measurements will cover the entire range of noise levels likely to be encountered in different business jets. To compensate for the lack of a comprehensive set of data, estimates were made of the range of noise levels likely to exist, and available data adjusted accordingly.

An indication of the likely range of operating conditions can be obtained from published airplane performance summaries (Anon 1980) where the information is usually divided into long range cruise and maximum speed cruise conditions. These (Anon 1980) data have been used to generate the cruise envelopes plotted in Figure 13 for current production business jet aircraft, excluding the Cessna Citation. The long range cruise speeds lie in the range of 390 to 435 knots, and the high speed cruise speed range is 425 to 490 knots. Cessna Citation speeds are significantly lower than those shown in the Figure 13.

Superimposed on the cruise performance envelopes is a third envelope containing the range of flight conditions associated with cabin noise measurements. A comparison of the envelopes shows that the test flight speeds correspond more closely to maximum speed cruise values than to the long range cruise conditions. Some adjustment of the acoustic data is needed to minimize this bias in the measurements. Details of the adjustment procedures are given in Appendix A.

2. Interior Noise Levels

Predicted average sound levels for the cabin and cockpit of business jet aircraft are shown in Figures 14 and 15,

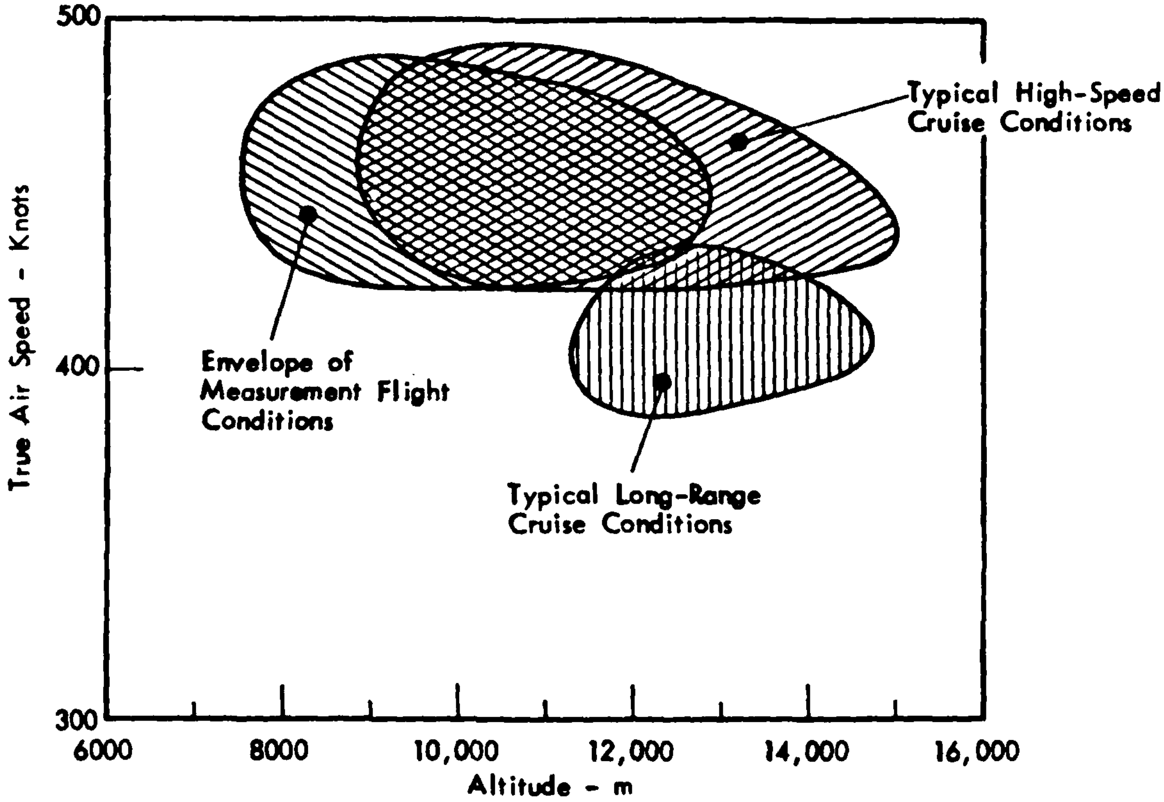


FIGURE 13. COMPARISON OF MEASUREMENT FLIGHT CONDITIONS WITH TYPICAL BUSINESS JET AIRCRAFT CRUISE CONDITIONS

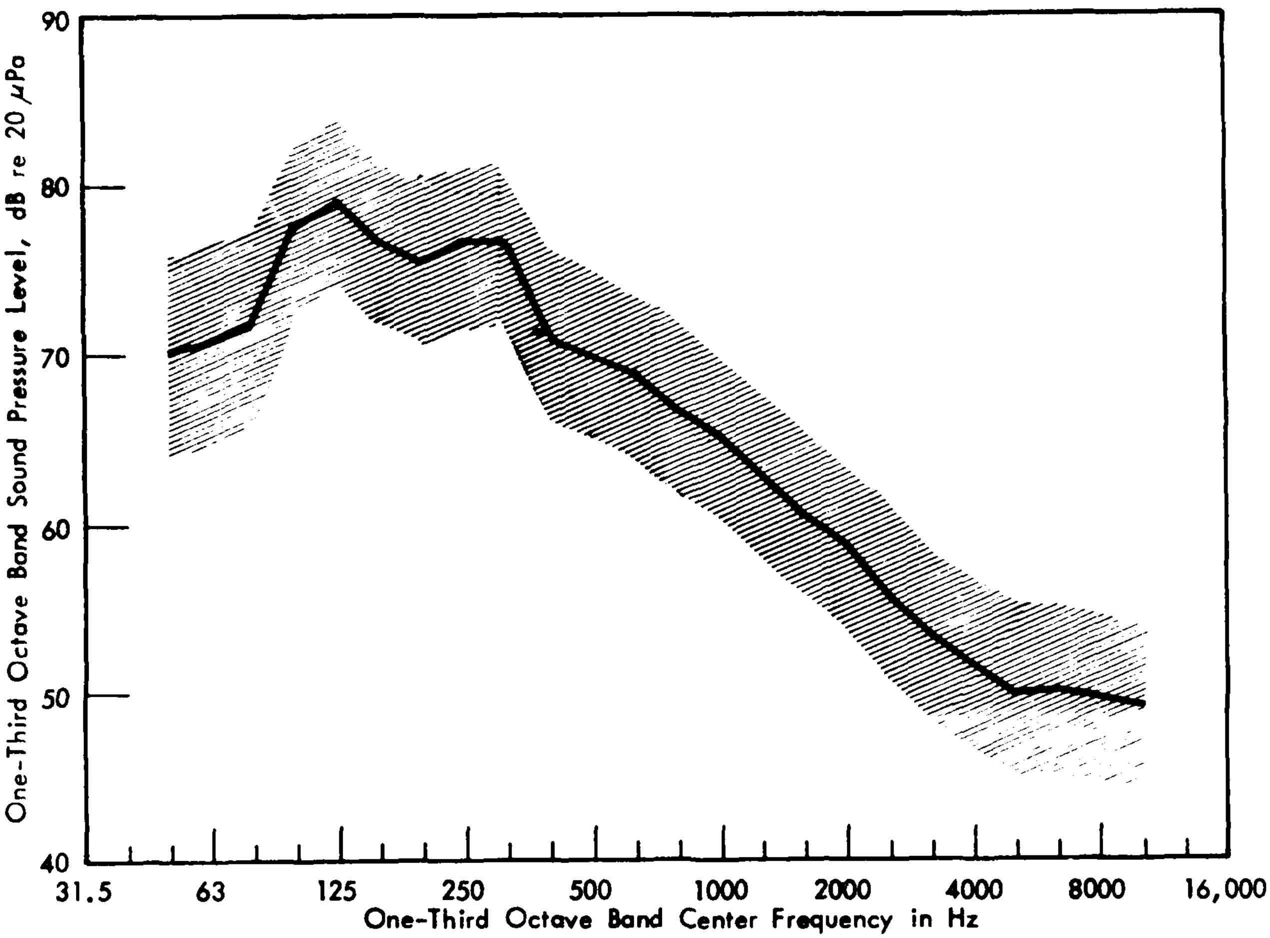


FIGURE 14. CABIN NOISE LEVELS FOR BUSINESS JET AIRCRAFT DURING CRUISE (MEAN ± ONE STANDARD DEVIATION)

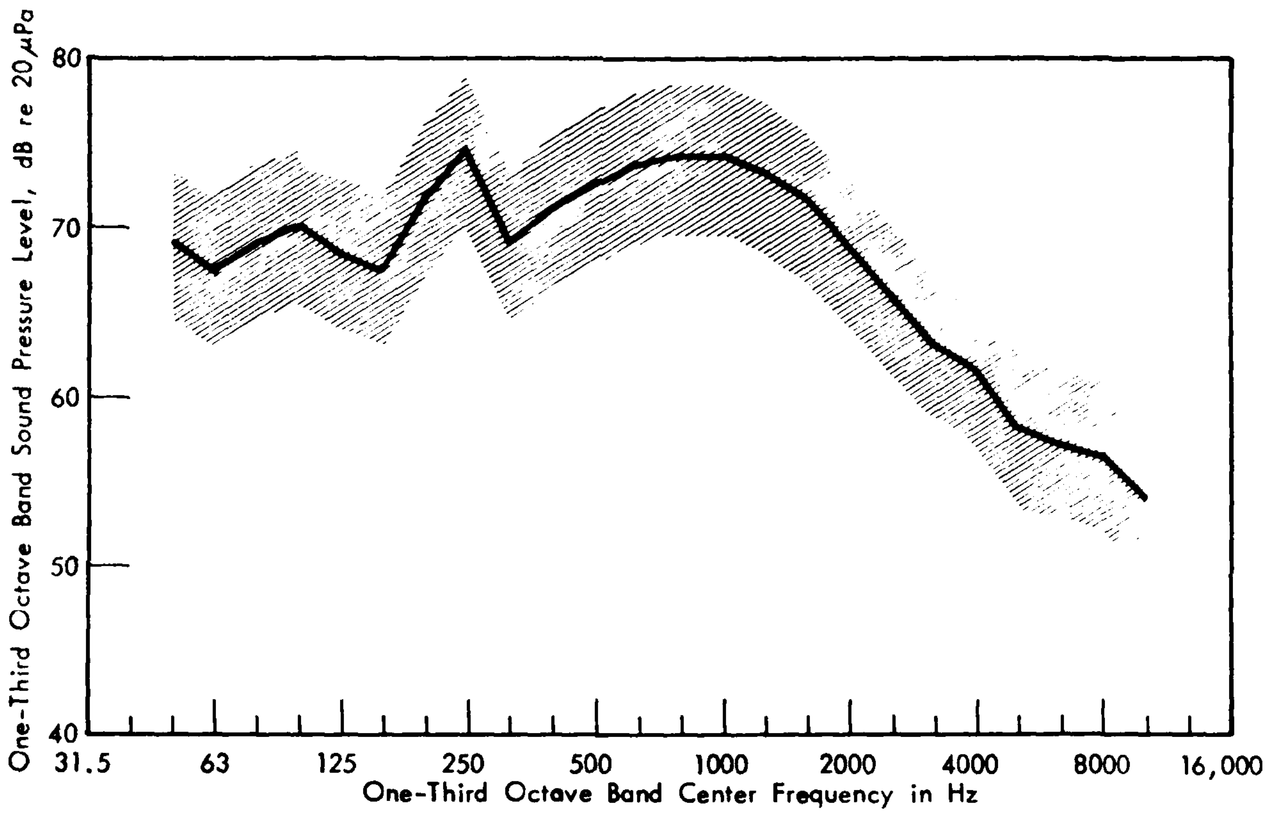


FIGURE 15. COCKPIT NOISE LEVELS FOR BUSINESS JET AIRCRAFT DURING CRUISE (MEAN ± ONE STANDARD DEVIATION)

respectively. Sound levels were measured at various locations in five different types of business jet aircraft, and the results adjusted as described in Appendix A to allow for a wider range of flight conditions. The values shown in Figures 14 and 15 are the adjusted values. The spectra have the same general trends as those shown in Figures 7 through 10 for commercial transports. Cabin sound spectra are dominated by low frequency components and cockpit spectra have relatively high sound levels in the mid to high frequency range.

Enroute climb and descent conditions for business jet aircraft will probably differ little from the cruise conditions considered in the analysis, since the cruise speeds included high speed as well as long range values. Thus it is reasonable to assume that the noise levels presented in Figures 14 and 15 will be similar to those encountered during climb and descent.

E. Short Takeoff and Landing (STOL) Aircraft

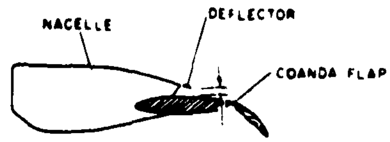
1. Airplane Characteristics

Jet-powered STOL aircraft have not yet advanced beyond the experimental phase, and there is no airplane of this type in commercial passenger-carrying service. However, several experimental jet-powered STOL aircraft have been tested in flight in the U.S.A. These aircraft include the Boeing YC-14 and McDonnell Douglas YC-15 aircraft which were built under the USAF Advanced Medium STOL Transport (AMST) program, and two C-8A aircraft modified for NASA.

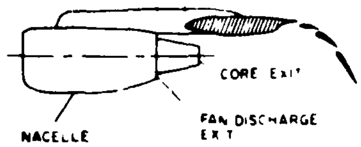
Several concepts have been considered for jet-powered STOL aircraft (NASA, 1972). These include the over-the-wing externally blown flap (OTW), alternatively known as upper surface blowing (USB), the under-the-wing externally blown flap (UTW or EBF), the internally blown flap (IBF) and the augmenter wing (AW) systems. These different concepts are shown diagrammatically in Figure 16.

The YC-14 and C-8A Quiet Shorthaul Research Aircraft (QSRA) come within the OTW or USB category, the YC-15 is in the UTW or EBF category, and the C-8A Augmenter Wing Research Aircraft is in the AW category. The test aircraft were all designed to demonstrate performance and handling characteristics with little regard to internal noise levels. However, some noise measurements were made in the cabin and on the surfaces of the airplane structures (Butzel et al., 1977; Shovlin, 1977; NASA, 1980). These data can be used as a basis for estimating typical noise levels in similar commercial aircraft. In addition use can be made of early predictions of interior and exterior surface noise levels for aircraft with USB and EBF powered-lift systems (Barton, 1975; Wilby et al., 1974).

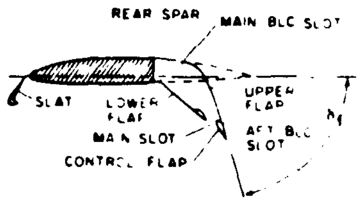
Several factors have to be taken into account in the prediction of typical cabin noise levels for STOL aircraft. First, typical commercial aircraft may be different in size from the test vehicles. Second, the interior noise time history for a typical STOL airplane flight will be different from that of a CTOL airplane flying a similar stage length. Third, commercial airplane designs will have fully-furnished interiors which the test aircraft did not have. Last, it is possible that some noise control



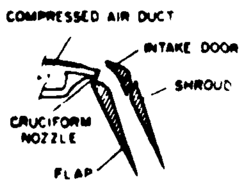
OVER - THE - WING / UPPER SURFACE BLOWN FLAP



UNDER - THE - WING / EXTERNALLY BLOWN FLAP



INTERNALLY BLOWN FLAP



AUGMENTER WING

FIGURE 16. STOL POWERED - LIFT SYSTEMS

features will be available by the time commercial aircraft designs are finalized, or at least by the time such aircraft enter service.

The size of a commercial jet-powered STOL aircraft will depend to some extent on the role for which it is designed. NASA (1972) studies include an aircraft with a takeoff weight of 68,000 kg (150,000 lb.) and a payload capacity of about 150 passengers for stage lengths of 150-1000 km (100 to 600 miles). This takeoff weight is similar to that of the YC-14 and it will be used for the purpose of the present study.

Falarski et al., (1975) specify typical thrust-to-weight (T/W) ratios for jet-powered STOL aircraft as follows:

USB and EBF Concepts:	T/W = 0.6 for takeoff	
	= 0.35 for approach	
IBF and AW Concepts:	T/W = 0.4 for takeoff	
	= 0.2 for approach	

The value of 0.6 for USB designs at takeoff condition is consistent with corresponding values for the YC-14 and C-8A QSRA aircraft, and the 0.4 ratio for the augmenter wing design is similar to that for the C-8A Augmenter Wing Research Airplane. Thus the thrust/weight ratios given by Falarski et al. will be assumed to be valid for hypothetical commercial transports. The assumed total thrust of engines for the hypothetical USB or EBF designs will then be 40,800 kg (90,000 lb.), and for the IBF or AW designs, 27,200 kg (60,000 lb.). The aircraft can have either two or four engines.

2. Prediction of Sound Levels

The approach followed in the prediction of cabin sound levels for hypothetical STOL aircraft is to first estimate the pressure levels on the exterior of the fuselage. Cabin sound levels are then estimated assuming that the noise control treatments are similar to those in current turbofan-powered aircraft. Then additional noise control treatments are postulated to reduce cabin noise levels to values comparable to those in current turbofan-powered airplanes.

Details of the prediction techniques are given in Appendix A.

3. Cabin Interior Noise Levels

The predicted interior sound levels for cabins of STOL aircraft are shown in Figures 17 and 18 for standard and improved sidewall treatments, respectively. These values are equivalent to average spectra presented in Figures 7, 9 and 14 for CTOL commercial and business jet aircraft. It is seen that when powered-lift devices are in operation (takeoff, climb and descent), the noise levels are dominated by low frequency contributions. Thus, it is difficult to achieve large decreases in the overall sound level. In cruise, the interior noise spectra are similar in shape to those in CTOL aircraft.

In the case of the narrow body, wide body and business jet aircraft, it was possible to estimate the likely variation (from seat to seat, and airplane to airplane) in sound level

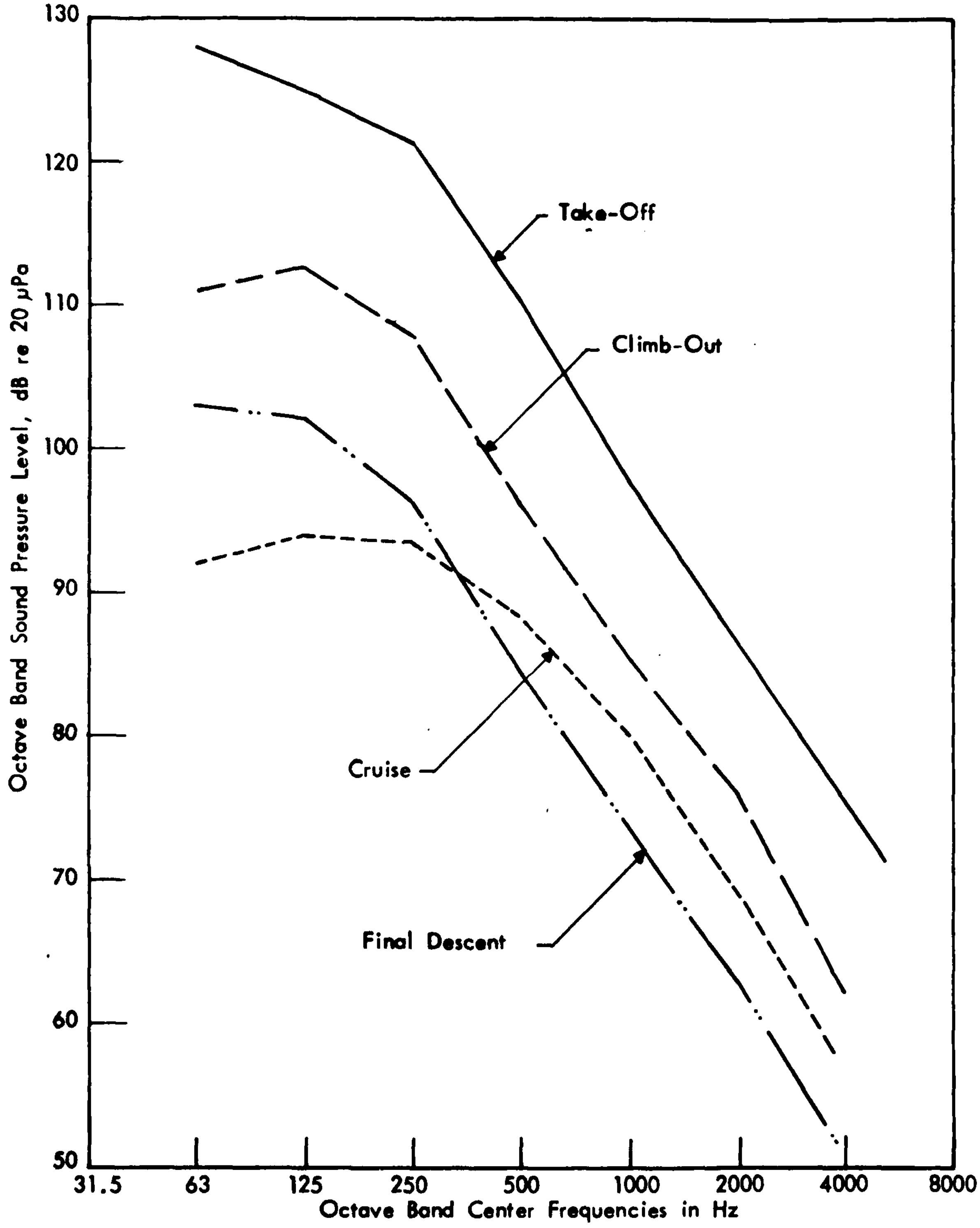


FIGURE 17. PREDICTED AVERAGE CABIN INTERIOR NOISE LEVELS FOR JET-POWERED STOL AIRCRAFT (STANDARD INTERIOR)

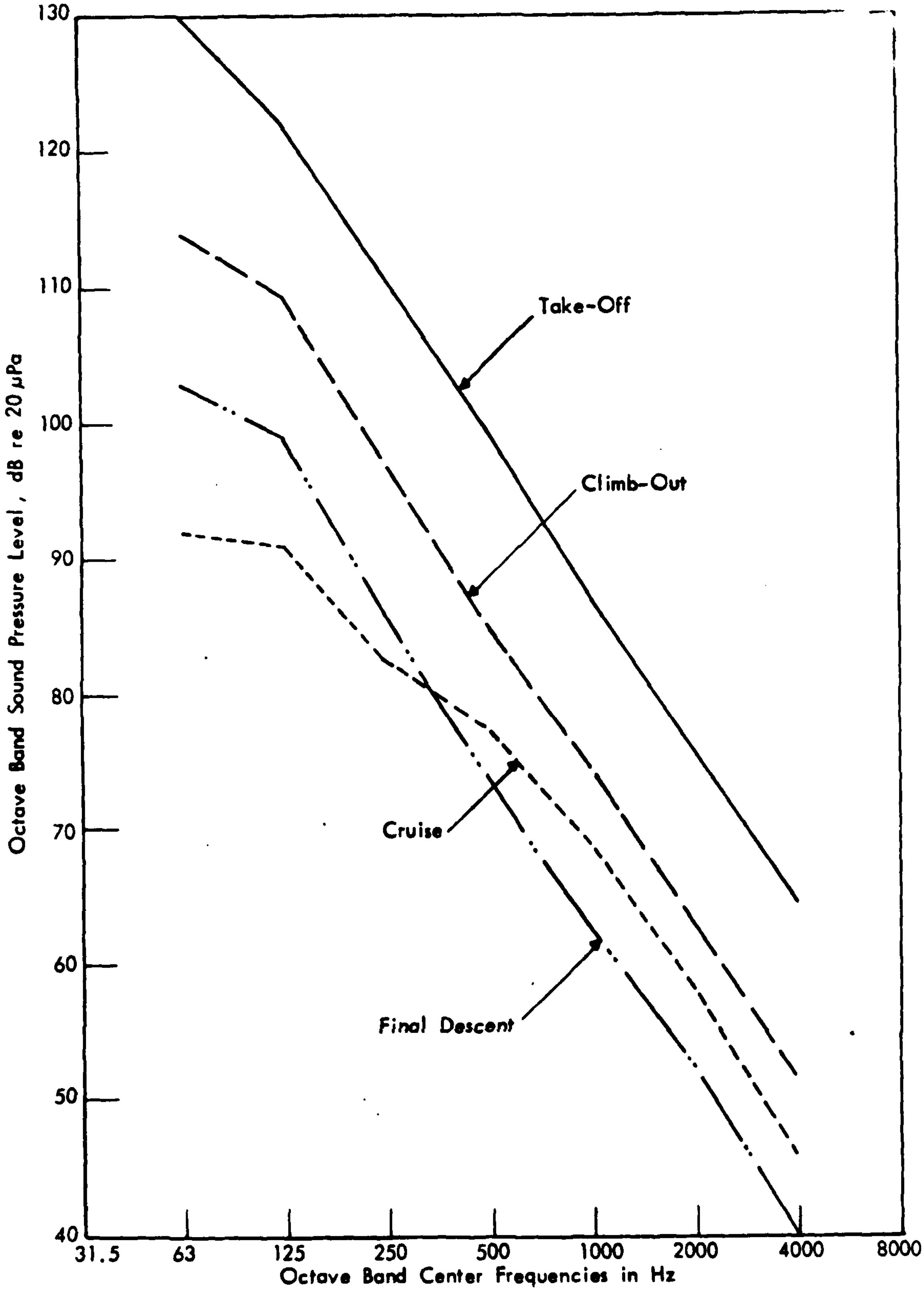


FIGURE 18. PREDICTED AVERAGE CABIN INTERIOR NOISE LEVELS FOR JET-POWERED STOL AIRCRAFT (IMPROVED)

about an average value in terms of standard deviations based on measured data. Such an approach is not possible for STOL aircraft, although it is probable that the variation in STOL interior noise levels will be similar to, or somewhat greater than, that for narrow body and wide body aircraft.

The sound level spectra present in Figures 17 and 18 include three flight conditions -- takeoff, climb-out, and final descent -- which were not considered for CTOL aircraft because of the relatively short operating time. These conditions are included for STOL aircraft because of the relatively high noise levels and the anticipation that they will occur for a longer time period than for CTOL operations. However, the total time during which powered lift devices are operated will still be a small fraction of the total flight time. En route climb and descent sound levels, which will exist for a somewhat greater fraction of the flight time, should be similar in value to those for cruise.

4. Cockpit Interior Noise Levels

Measurements on the exterior of STOL aircraft show that, when powered-lift systems are operated, the noise levels decrease significantly as the microphone location moves toward the nose. The decreases in sound level vary from 5 to 25 dB, depending on flight condition, with an average change of about 15 dB. Thus, the cockpit sound levels should be lower than the average levels in the cabin although the differences between cabin and cockpit will probably be less than in CTOL commercial transports because the influence

of the powered lift systems extends much further forward than does engine noise in CTOL aircraft under similar flight regimes.

In cruise, since STOL powered lift systems are not in use; the cockpit noise levels will be determined to a large extent by flow conditions over the forward fuselage, as is the case for CTOL commercial transports. There may, however, be low frequency engine noise effects when engines are installed close to the forward fuselage structure, as in the case of the Boeing YC-14 airplane.

Estimates of cockpit sound levels in typical STOL transport aircraft have been obtained using estimated cabin sound levels from Figures 17 and 18 and measured cockpit sound levels for CTOL commercial transports (Figures 7 and 9). For takeoff, climb-out and descent with powered lift systems operating, it is assumed that cockpit noise levels are about 15 dB lower than average sound levels in the cabin with standard treatment. During cruise it is assumed that low frequency sound levels are about 10 dB lower at low frequencies, and similar to corresponding CTOL sound levels at high frequencies. The resulting sound pressure spectra are shown in Figure 19 for the flow flight conditions takeoff, climb-out, cruise, and descent.

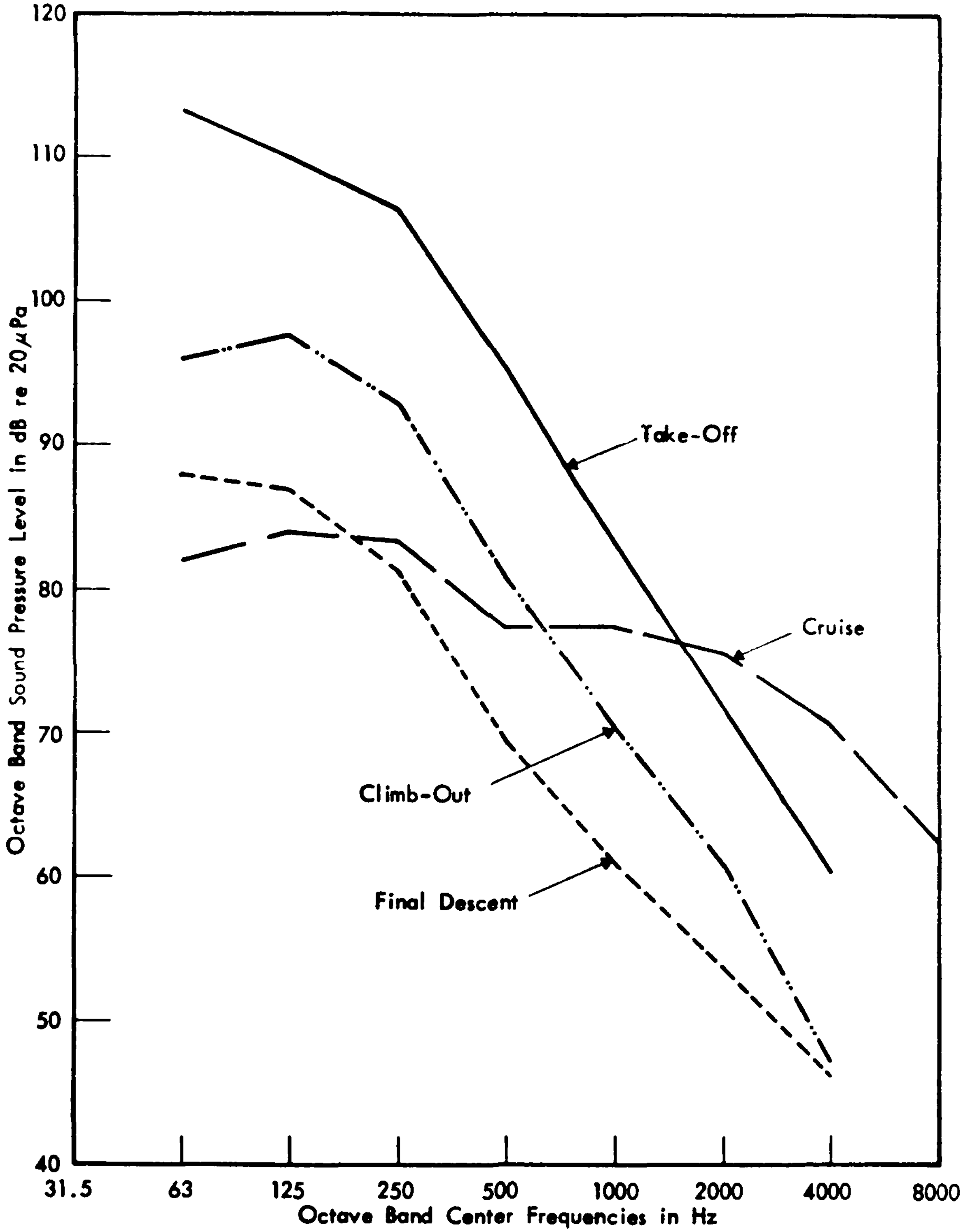


FIGURE 19. PREDICTED AVERAGE COCKPIT INTERIOR NOISE LEVELS FOR JET-POWERED STOL AIRCRAFT

IV. TIME EXPOSURE

A. Commercial Aircraft

The amount of time which pilots and crew are exposed to interior aircraft noise varies from day to day, and even week to week. However, for Part 121 operations, FAA has placed an upper limit of 1000 hours per year as the maximum amount of time that pilots and crew may fly because of possible fatigue (FAA 1980). Recent suggested changes may eliminate the thousand hours per year maximum and replace it by daily, weekly and monthly limits (DOT 1980). The proposed limits would be 110 hours in any thirty-day period, or forty hours in any seven-day period. Daily exposures could be as long as sixteen hours. However, rest time must be no less than duty time and on average the rest time will be at least twice the duty time.

The 110 hours in a thirty-day period is equivalent to five hours per day assuming a five-day work week. However, pilots' unions contracts limits the time to no more than 85 hours per month which is equivalent to a four-hour exposure per day over each work day.

B. Business Jet Aircraft

In the case of crew members of business jet aircraft, estimates of the noise exposure times can be deduced from available information regarding airplane utilization and typical pilot staffing. Estimates from FAA aviation forecasts (FAA 1979) indicate that for the year 1975 the average utilization of business jet aircraft was 500 hours per year. The corresponding figure for 1979 was 538 hours per year; for 1999 estimates

suggest 547 hours per year. Utilization by type of aircraft for 1979-1980 is indicated in Table I (Anon 1980B). The average utilization rate of 535 hours per year, shown in the table, is very close to the FAA value of 538.

The average pilot staffing of a business aircraft flight department is about 2.3 pilots per aircraft (Anon 1980B). Taking this staffing ratio and an aircraft utilization rate of 538 hours per year results in an average exposure (flight) time of about 1.8 hours per working day. If a more conservative approach is taken, and it is assumed that there are only two pilots per aircraft (i.e., the same two pilots fly the airplane throughout the year) the daily exposure is about two hours.

C. Short Takeoff and Landing (STOL Aircraft)

Since no STOL aircraft are in routine commercial service at this time, it is difficult to anticipate the actual exposure time which might be experienced by pilot and crew. An exposure time the same as current commercial aircraft (an average of four hours per day) would represent an upper limit of exposure time. It is further assumed that on average, the flights would be one hour in duration and, therefore, it is anticipated that four takeoffs and landings would be experienced on an average daily basis.

D. Passenger Exposure Times

There are no upper limits for passenger exposure times. However, average passenger flight times are two to three hours per year (Anon 1978). This is less than 0.3 percent of the maximum allowed for pilots and crew. Of course,

TABLE I ANNUAL BUSINESS JET UTILIZATION BY AIRCRAFT TYPE

Aircraft Type	Average Hours Flown Per Year
Gulfstream II	732.8
JetStar	438.8
Falcon	486.0
HS 125	480.0
Sabreliner	569.8
Westwind	518.9
Learjet	567.1
Citation	486.2
Average	535.0

some people fly a great deal more than this: one airline estimates only 5% of all passengers fly over 100,000 miles per year. Even this is only one-fourth the estimated maximum for pilots and crew.

V. HEARING DAMAGE RISK FOR AIRCRAFT

Knowing the noise levels and exposure time, it should be a simple matter to determine whether or not the levels established by CHABA and presented in Figures 1 through 4 are exceeded. However, are the results of applying the extrapolated CHABA method valid? The flight schedules of pilot and crew are not as routine as the five-day, forty-hour-per-week work schedules for which the levels established by CHABA are intended. Pilots and crew may work as long as sixteen hours on a single mission. To account for these longer work hours, the damage risk contours are extrapolated to include exposures as long as sixteen hours as shown in Figure 4.

Some concern may exist for the sixteen hour extrapolation since recovery time for sixteen hour daily exposures is limited to only eight hours while the original daily exposure time of eight hours allowed a recovery time of sixteen hours (twice exposure time). Recent tests (Melnick, 1976; Mills, 1976) for long exposure indicate that the amount of TTS reaches a maximum after about eight to twelve hours exposure. Thus the TTS that would occur for sixteen hours exposure would be little greater than that for eight hours. However, the longer the exposure time the longer time needed for recovery from TTS. In fact, recovery time is one to two times as long as exposure time. If recovery time is repeatedly insufficient to allow threshold to return to normal, then

permanent threshold shift may occur. Fortunately, the schedule for the pilots and crew allows a recovery time of at least twice the exposure time (actually five to six times) over a one month duty time. Of course the noise levels during recovery time would have to be less than exposure levels and no greater than 8 hour damage risk contour in order for the recovery period to be effective. The five-day, forty-hour-per-week worker has a recovery period just twice as long as the exposure period. Weekend nonexposure periods are assumed for both pilots and crew as well as the forty-hour-per-week worker.

Thus, although the pilots and crew may be exposed on certain days for longer exposure periods than the forty-hour-per-week worker, the average total exposure is much less (four hours per day). Therefore, all determinations for pilots and crew including cabin attendants of commercial airlines will be made using the four hours per day exposure (85 hours per month). Even this figure is a maximum and higher than the normally reported exposure time of 70 hours per month (private communications with airline pilots and officials). The non-union pilots and crew would be limited to five hours per day by conforming to FAA regulations. Similar determinations to those cited below could equally well be made for these exposures. However, since the majority of commercial pilots are union, the four hour exposure day was used.

A. Narrow Body Aircraft

Comparing the levels shown in Figures 7 and 8 for narrow bodied aircraft, both in the cabin and in the cockpit, with the damage risk contour for four hours per day exposure, one notes that the interior noise is substantially below the

damage risk contour as shown in Figures 20 and 21. The noise level for the cabin is 14 dB below the damage risk contour at 1000 Hz. However, the interior aircraft noise is not always at the average level, but in certain situations and locations it is either above or below the average level. An estimate of the percentage of situations which might exceed the damage risk contour has been made and is indicated in Figures 20 and 21. The determination was made by noting the number of standard deviations by which the damage risk contour exceeded the average cabin noise and determining the percent of cases which would exceed this contour in a Gaussian distribution.

For example, the damage risk contour exceeded the cabin noise by 14 dB which was 3.5 standard deviations higher than the average. Tables of the normal distribution indicate that 3.5 standard deviations is exceeded only 0.02% of the situations. Similarly, for cockpit noise, the percent of situations exceeding the damage risk contour is only 0.0006%. A summary of this information is provided in Table II for all aircraft types under evaluation.

The finding that the aircraft noise levels are below the 4-hour damage risk contour is further supported by Mabry (1979) who found no TTS for 4-hour exposures to aircraft interior noise.

Interior aircraft noise exposure for passengers in narrow bodied aircraft is much less than for pilots and crew. Since the exposure for passengers is only a small fraction of the exposure for the pilots and crew, determination of the percent of situations exceeding the damage risk contour is too small to estimate reliably. In practice, no situation exists

TABLE II ESTIMATE OF PERCENT OF AIRCRAFT INTERIOR LOCATIONS WHICH EXCEED APPROXIMATE DAMAGE RISK CONTOUR

Aircraft Type	Cabin/ Cockpit	Avg. Daily Exposure	Amt. Interior Noise is Below Damage Risk Contour	Freq.	Standard Deviation of Interior Noise	No. of Std. Deviations Below Damage Risk Contour	Est. Percent Exceeding Contour
Narrow Body	Cabin	4 hours	14 dB	250 Hz.	4.0 dB	3.50	0.02%
Narrow Body	Cockpit	4 hours	10 dB	1000 Hz.	2.6 dB	3.85	0.006%
Wide Body	Cabin	4 hours	16 dB	250 Hz.	4.0 dB*	4.00	0.003%
Wide Body	Cockpit	4 hours	15 dB	2000 Hz.	3.5 dB*	4.3	0.0009%
Business Jet	Cabin	2 hours	12.5 dB**	315 Hz.	5.0 dB	2.5	0.6%
Business Jet	Cockpit	2 hours	12.5 dB	1250 Hz.	4.5 dB	2.78	0.3%
STOL	Cabin	4 hours	2.5 dB	250 Hz.	4.0 dB	0.62	26.8%
STOL	Improved Cabin	3 min. takeoff	7 dB	63 Hz.	4.7 dB	1.49	6.8%
STOL	Cockpit	4 hours	12.5 dB	250 Hz.	3.9 dB	3.21	.07%

* Estimated From Upper Half of Distribution Since Distribution Was Skewed

**Using Contour For Tone From Figure 2

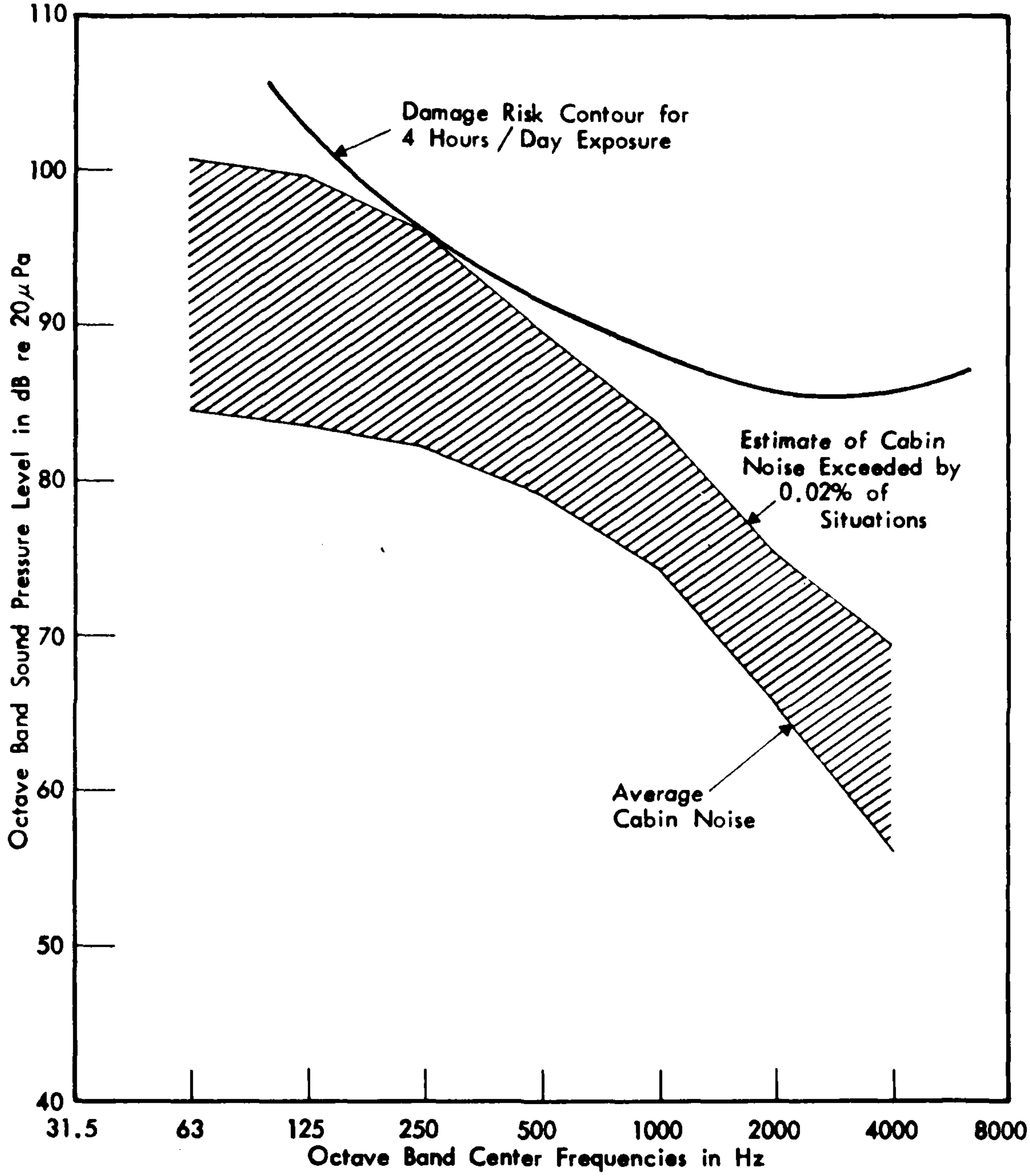


FIGURE 20. COMPARISON OF 4 HOUR DAMAGE RISK CONTOUR AND CABIN NOISE IN NARROW BODY AIRCRAFT DURING CRUISE

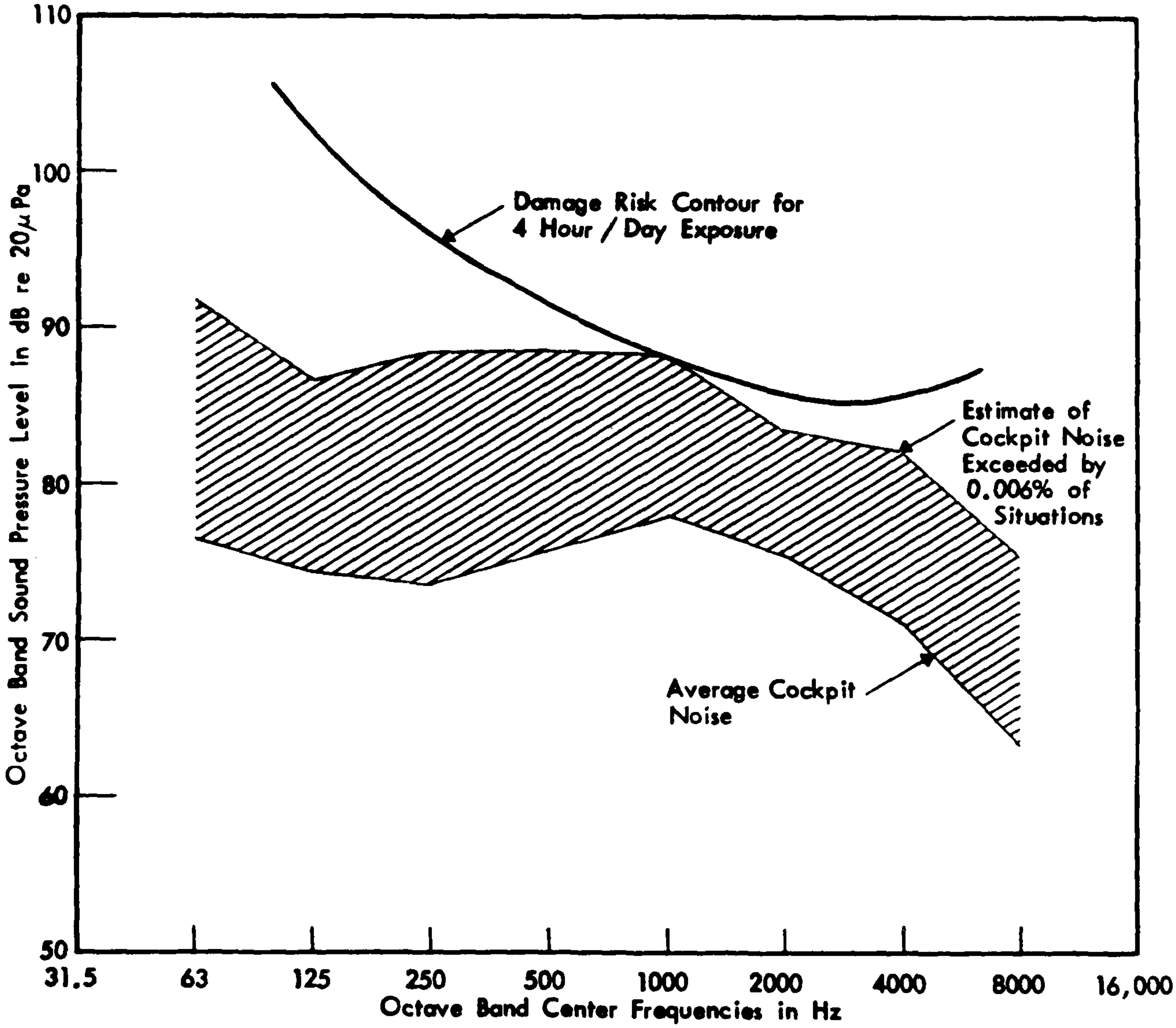


FIGURE 21. COMPARISON OF 4 HOUR DAMAGE RISK CONTOUR AND COCKPIT NOISE IN NARROW BODY AIRCRAFT DURING CRUISE

which would be higher than the damage risk contour for 1-1/2 minutes per day (4.3 hours per month) which is still greater than the two to three hours per year average passenger flight time.

Figure 11 indicates that the levels for climb and descent are comparable to those found for cruise in the narrow bodied jet aircraft. Further, it is estimated that the amount of time spent in either climb or descent conditions is about one hour per day (15 minutes per flight). The one hour per day assumes an average of four flights during the four hour period estimated as daily flight time for pilots and crew. Thus, even if the levels for the climb or descent situations were greater than for cruise, the reduced time spent in climb or descent conditions would allow higher levels shown by the one hour per day damage risk contour in Figure 4. The only cause for concern might be the high speed descent condition. For this condition, it is estimated that the levels shown in Figure 12 are experienced for 9 to 10 minutes per flight and/or approximately 40 minutes per day assuming four flights per day. The levels for this condition are 4.5 dB higher than for cruise at both 2000 and 4000 octave band frequencies. The appropriate damage risk contour on the other hand is elevated by 7 dB and 6 dB, respectively, for the 2000 and 4000 Hz octave band frequencies. Thus, the damage risk contour is elevated more than the increase in levels associated with the high-speed descent which means that the cruise condition still controls the noise exposure experienced by the pilots and crew.

B. Wide Body Aircraft

The comparison of levels in wide body jet aircraft to the damage risk contour is similar to that for the narrow body

aircraft. The damage risk contour is that shown in Figure 4 for four hours, and the levels for the wide bodied aircraft are shown in Figures 9 and 10. However, the standard deviation determined for Figures 9 and 10 were not employed in the determination because of their non-normal distribution. The greater number of quiet situations in the wide bodied aircraft created proportionally more quiet than noise situations. This in turn resulted in a high standard deviation controlled by quiet situations rather than noisy ones. Using the noisier levels (those above the average) a new standard deviation was estimated to allow determination of the percent of situations exceeded. The result is that for wide bodied aircraft during cruise the interior levels were 16 dB below the damage risk contour for the cabin and 15 dB below the damage risk contour for the cockpit. This information along with the estimated standard deviation of 4.0 and 4.3 dB, respectively, were used to determine that .003% of the situations for aircraft cabin interiors and .009% for cockpit interiors exceeded the four hour damage risk contour.

Situations during climb and descent like those found in the narrow body aircraft situation were not expected to control the total noise exposure insofar as hearing loss is concerned for pilots and crew of wide bodied aircraft. Again, a complete tabulation of all of the damage risk determinations may be found in Table II for narrow body, wide body, business jet and STOL aircraft.

It is anticipated that as in narrow bodied aircraft, hearing damage risk to passengers would be far less than that for the pilot and crew. In no case would the levels experienced by passengers exceed the 1-1/2 minute damage risk contour equivalent to 4.3 hours per month.

C. Business Jet Aircraft

The hearing damage risk associated with business jet aircraft is determined somewhat differently from those of the commercial aircraft. In the first place, the average daily exposure for business jet aircraft is two hours rather than the four hours associated with commercial jet aircraft. Also, in the business jet aircraft, tones exist at several frequencies included in the 1/3 octave bands with center frequencies from 100-315 Hz, which requires the use of the damage risk contours determined for tones rather than broadband noise. In business jet cabins, tones control the exposure. The level of the cabin interior is 12.5 dB below the damage risk contours for a tone at 315 Hz. Using the standard deviation of 5, it is found that 0.6% of the situations exceed the damage risk contour.

However, this is a very conservative figure for those normally riding in business jet aircraft since no cabin attendants are required. The passengers are not exposed to 2 hours per day flight time. For the cockpit, the level is 12.5 dB below the damage risk contour at 1250 Hz.

This situation is for broadband noise since the pure tones do not control in this particular situation. The estimated percent of situations exceeding the contour is .3% as shown in Table II.

D. Short Takeoff and Landing Aircraft

Levels associated with the STOL aircraft during cruise are much greater than those for the other categories of aircraft under investigation. Since no exposure information is available for this type of aircraft, a time duration of four hours is used which is the same as for commercial aircraft limits discussed previously. The levels for the cabin are only 2.5 dB below the damage risk contour at 250 Hz. This means that 26.6% of the situations would probably exceed the damage risk contour. In an improved version of the cabin, the level during cruise would be 11.5 dB below the damage risk contour at 125 Hz. Thus for the improved situation the percent of cases exceeding the damage risk contour is only .7%. However, the improved cabin environment still has a fairly high interior level during takeoff which is estimated to take 30 to 45 seconds for each takeoff. Using the assumption of four takeoffs per day gives a total of three minutes exposure. The damage risk contour exceeds the level in the improved cabin by 7 dB at 63 Hz resulting in an estimated 6.8% of the situations which would exceed the damage risk contour. This is the only case in all of the aircraft interiors evaluated in which a non-cruise condition dominates the damage risk exposure.

For the cockpit interior, levels are lower than the damage risk contour by 12.5 dB at 250 Hz. Thus, .07% of the situations found in the cockpit would exceed the damage risk contour.

VI. CONCLUSIONS

The following conclusions may be drawn as a result of investigations and analysis performed under the study of interior aircraft noise:

1) The procedure for estimating hearing damage risk recommended by the Committee on Hearing Bioacoustics and Biomechanics (CHABA) appears adequate for evaluation of potential hearing loss in jet-powered aircraft. The adequacy is confirmed by recent tests involving long exposures to noise and the associated TTS. Long exposure durations of 16 hours flight time should not present problems in utilizing the CHABA recommendations as long as the average daily exposure is four hours or less. Four hours is currently the maximum average daily amount flown in commercial jet aircraft. Potential hearing loss in business jet aircraft may be evaluated by assuming an average of two hours of exposure time per day cockpit personnel. Special situations may require lower limits if exposure times greater than two hours are incurred on a daily basis.

2) Potential hearing loss evaluations may be based on interior aircraft levels measured during the cruise operation in both commercial and business jet aircraft. However, the high levels associated with takeoff of STOL

aircraft, in some cases, may govern the exposure potentially responsible for producing hearing loss.

Since the STOL aircraft levels were estimated, it is recommended that when commercial aircraft of this type are available, careful interior measurements be made and a re-evaluation of potential hearing loss be conducted.

3) None of the average levels found in commercial or business jet aircraft exceeded the damage risk contours recommended by CHABA. In commercial aircraft, both wide body and narrow body, and in both cockpit and cabin locations less than 0.1 percent of the situations are expected to exceed the CHABA damage risk contours. Similarly, in business jet aircraft less than 1% are expected to exceed the damage risk contours.

4) Because of the small percentages of situations in commercial aircraft expected to exceed the damage risk contours for pilots and crew, it is unlikely that any passenger will be exposed to situations which would exceed the damage risk contour in either wide or narrow body aircraft. A passenger would need to fly at least 400,000 miles per year over 10 years to attain exposures equivalent to the exposures of airline crews.

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APPENDIX A

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APPENDIX A

EXTRAPOLATION AND PREDICTION PROCEDURES FOR AIRCRAFT INTERIOR NOISE

APPENDIX A

EXTRAPOLATION AND PREDICTION PROCEDURES FOR AIRCRAFT INTERIOR NOISE

This Appendix provides the extrapolation techniques used to convert measured interior noise levels associated with certain aircraft operating conditions to those associated with certain aircraft operating conditions for commercial jet aircraft and business jet aircraft. The techniques were necessary in order to produce a range of levels associated with the various operating conditions presently in use for these types of aircraft. In addition, techniques for predictions of interior noise levels for STOL aircraft are described.

A-1. Commercial Jet Aircraft

The main noise sources in commercial transports are the external turbulent boundary layer, jet engines and air conditioning. Except at the rear of the cabin, the dominant source is usually the turbulent boundary layer and a prediction procedure can be developed for this source, so that sound levels can be estimated for other flight conditions. Bray (1974) obtained an empirical relationship for cabin A-weighted sound level (L_A) as a function of airplane altitude (h):

$$L_A = 87 - 0.95h \text{ dB}$$

where h is in km. This relationship does not take airplane speed into account, except implicitly in its relationship with altitude. A more detailed relationship is required. It is known from a number of experiments (Ungar et al., 1977) that the rms fluctuating pressure ($\bar{p}$) for the turbulent boundary layer approximately proportional to the flight dynamic pressure (q). Thus $\bar{p}$ is proportional to the ambient exterior density (ρ) and the square of the flight speed (V).

In the frequency domain, pressure spectra can be scaled in terms of the non-dimensional frequency $\omega\delta/V$, where δ is the boundary layer thickness. Thus, as V increases, energy shifts to higher frequencies and as δ increases energy shifts to lower frequencies. The net result is that at low frequencies the mean square pressure varies as V^n, where $n < 4$ and at high frequencies as V^n, where $n > 4$.

Cabin sound levels will be influenced to some extent by the transmitting fuselage structures, but assuming that there is no strong coincidence effect, variation of sound level with velocity should not be too dissimilar from that for the

exterior pressure. Review of cabin noise levels for a number of commercial transports and business jets show that, at least for higher frequencies, the measured variation of cabin sound pressure level with aircraft speed can be represented reasonably well if n is given the value 4.5. This value for n is used in the present study throughout the frequency range of interest, when it is necessary to extrapolate measurements to other flight conditions.

A-2. Business Jet Aircraft

Noise levels in the cabin and cockpit of a business jet airplane are usually determined by the external aerodynamic pressures, structure-borne vibration from the engines, and interior air conditioning. Engine and air conditioning noise levels can vary somewhat randomly from airplane to airplane, and they cannot be predicted with any great degree of confidence. Aerodynamic noise does, however, show a general trend of increasing with flight dynamic pressure. Thus it is possible to make adjustments to the data to account for changes in flight speed and altitude.

A coarse scaling of interior noise level can be made using the same approach as that adopted for commercial jet transports whereby the sound pressure in the cabin or cockpit is assumed to vary as ambient density to the first power, and aircraft true airspeed to the power 2.25. This scaling is applied throughout the frequency range of interest, although it is recognized that at frequencies below about 500 Hz the interior sound levels are probably dominated by engine noise.

When the interior noise scaling procedure is applied to the long range and high speed cruise conditions given in Figure

13 (reproduced here as Figure A-1), the estimated noise levels lie in a range of ± 5 dB relative to the values for a typical cruise condition with a flight speed of 215 m/s (700 ft/sec) at an altitude of 35,000 feet. However, review of the available noise measurements indicates that the data are associated mainly with high-speed cruise. Using the preceding scaling procedure, it is estimated that the average sound levels determined from the measurements should be reduced by about 3 dB in order to be representative of average sound levels for the complete range of possible cruise conditions.

A-3. STOL Aircraft

A(a). *Exterior Noise Levels*

The four flight regimes of interest for STOL airplanes are takeoff, initial climb, cruise, and final descent and approach. STOL devices will be used during all these regimes except cruise. Fuselage surface pressure fluctuations on several airplanes have been measured for one or more of these flight conditions (Butzel et al., 1977; Shovlin, 1977; NASA 1980). These pressures have been scaled to the common baseline airplane having a takeoff weight of 68,000 kg (150,000 lb). In the scaling it has been assumed that changes in thrust are achieved by changes in engine airflow and diameter. Thus the engine-generated noise levels will change as the square of engine diameter and the characteristic frequencies of the pressure spectra will vary inversely with diameter. In adopting this approach it is assumed that noise levels generated by interaction between engine exhaust and airplane structure will scale

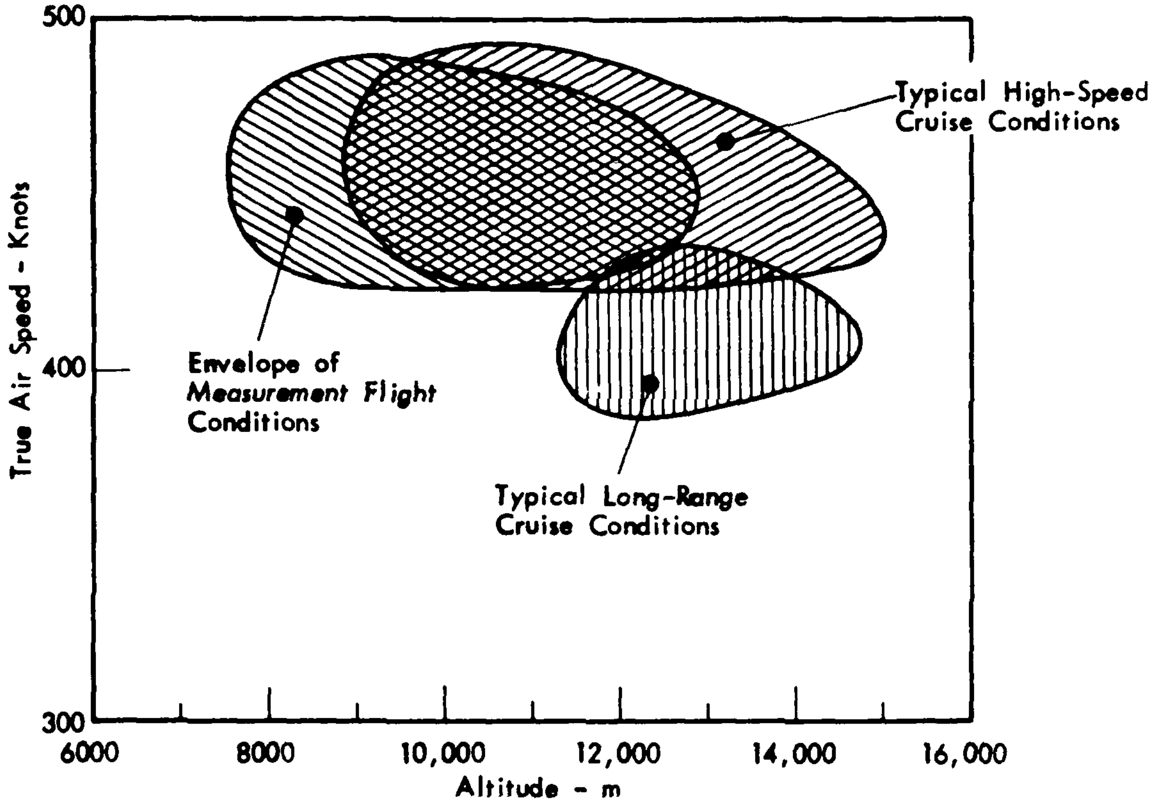

FIGURE A-1. COMPARISON OF MEASUREMENT FLIGHT CONDITIONS WITH TYPICAL BUSINESS JET AIRCRAFT CRUISE CONDITIONS

in the same manner as jet exhaust noise. This is a reasonable assumption since wing and flap dimensions will change with airplane size.

Figures A-2 through A-5 present a summary of the exterior pressure level data for jet-powered STOL airplanes adjusted to a takeoff weight of 68,000 kg. The two-engine YC-14 (USB) airplane is represented only for initial climb. Data for the C-8A augmenter wing airplane are available only for the takeoff condition. No scaling adjustments have to be made to the YC-14 data; there is a 4.5 dB adjustment made to the QSRA data and a 7 dB modification to the C-8A augmenter wing data. The frequency shifts for QSRA and augmenter wing aircraft were two and three one-third octave frequency bands, respectively. The data are presented as spectral bands encompassing a range of measurement locations.

Takeoff pressure levels in Figure A-2 are associated with the moment of brake release, and the highest levels exist for only a short period of time. Pressure levels for the 2-engined USB airplane are similar to those for the 2-engined augmenter wing design, except that in the latter case there is relatively more energy at high frequencies and less at low frequencies. The band of data is narrow for the augmenter wing airplane because measurements are presented for the rear of the cabin only. The upper bound of the USB pressure levels agree closely with values predicted by Barton (1975) for USB and EBF aircraft. Figure A-2 also presents sound pressure levels for CTOL aircraft at fuselage locations aft of the wing-mounted engines. The spectra show that the STOL designs are associated with much higher pressure levels, particularly at low frequencies.

The spectrum levels decrease as forward speed increases. Thus the pressure levels in Figure A-3 for the 2-engined USB design

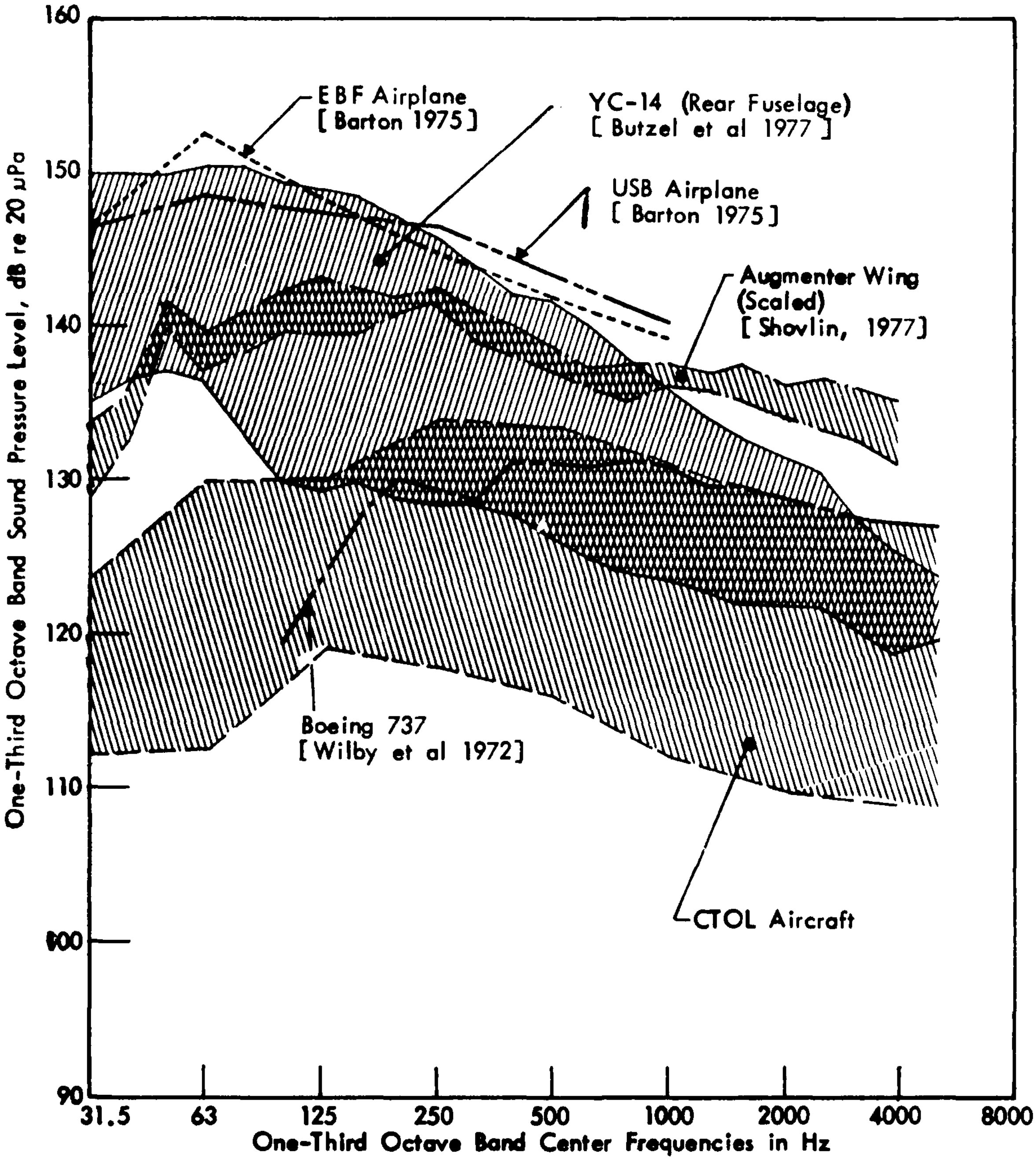

FIGURE A-2. EXTERNAL SOUND PRESSURE SPECTRA: REAR FUSELAGE AT TAKE-OFF, SCALED TO 150,000 lb T/O WEIGHT AIRPLANE

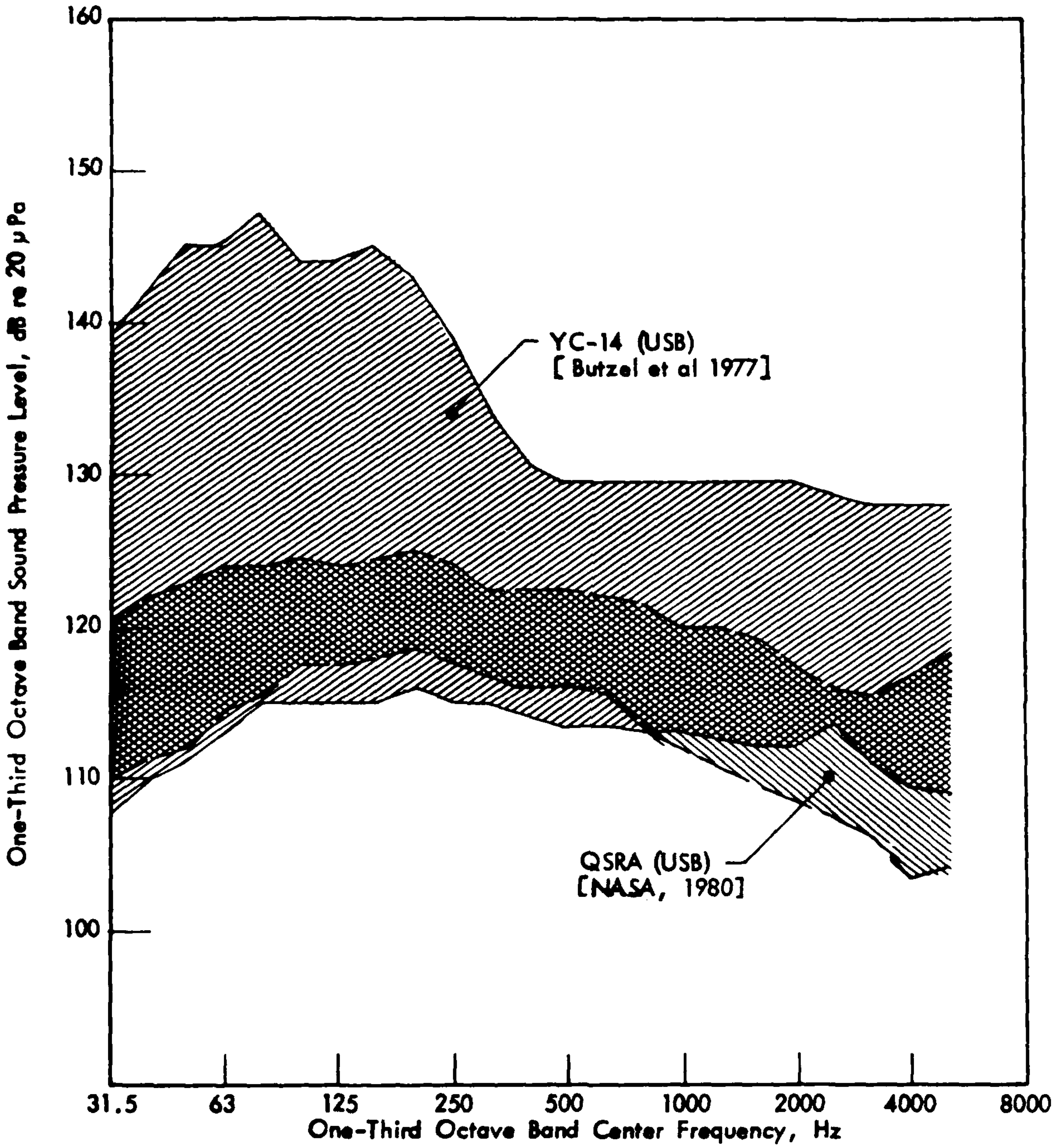

FIGURE A-3. EXTERNAL SOUND PRESSURE SPECTRA: CLIMB-OUT SCALED TO 150,000 lb T/O WEIGHT AIRPLANE

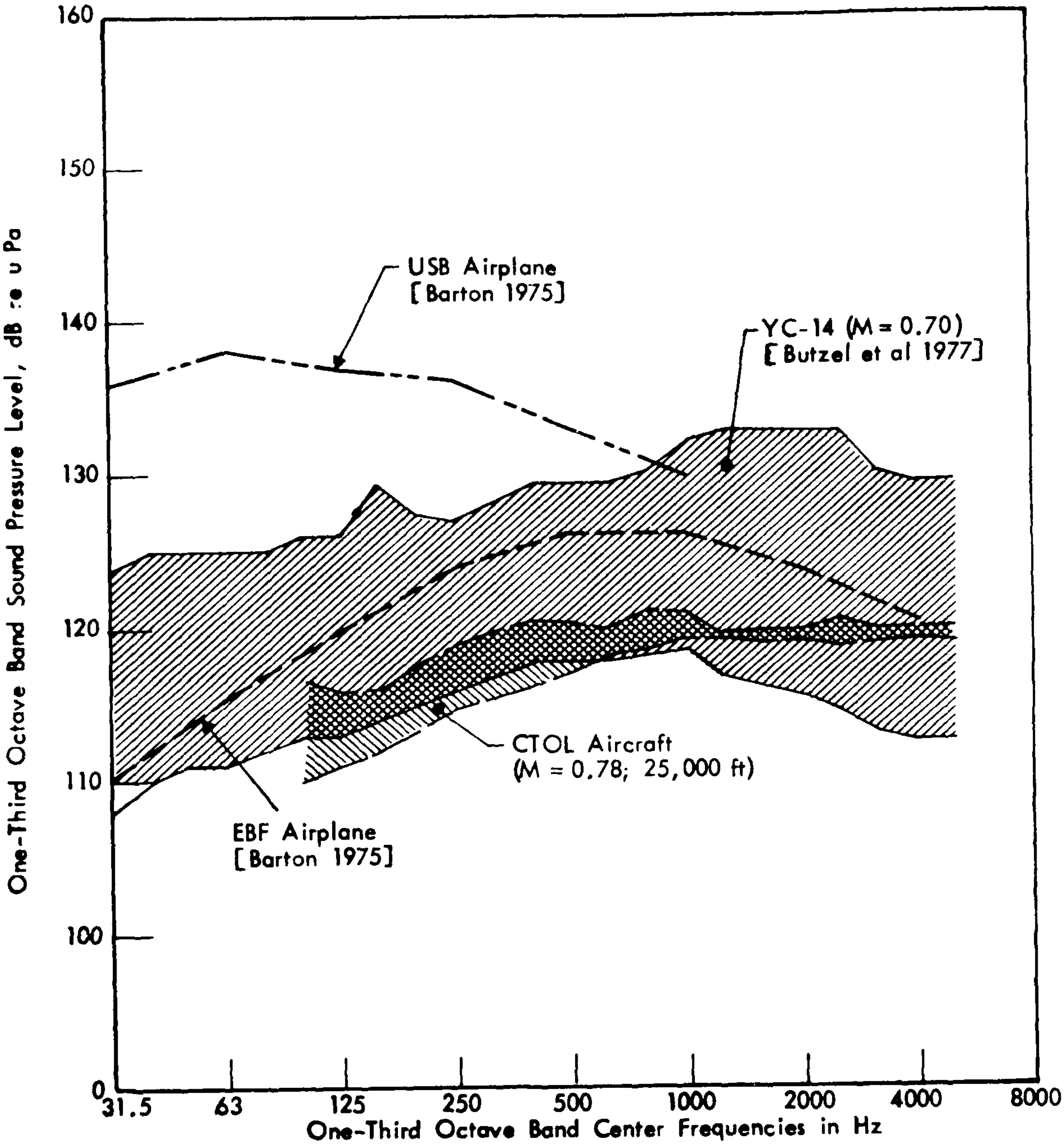

FIGURE A-4. EXTERNAL SOUND PRESSURE SPECTRA: CRUISE SCALED TO 150,000 lb T/O WEIGHT AIRPLANE

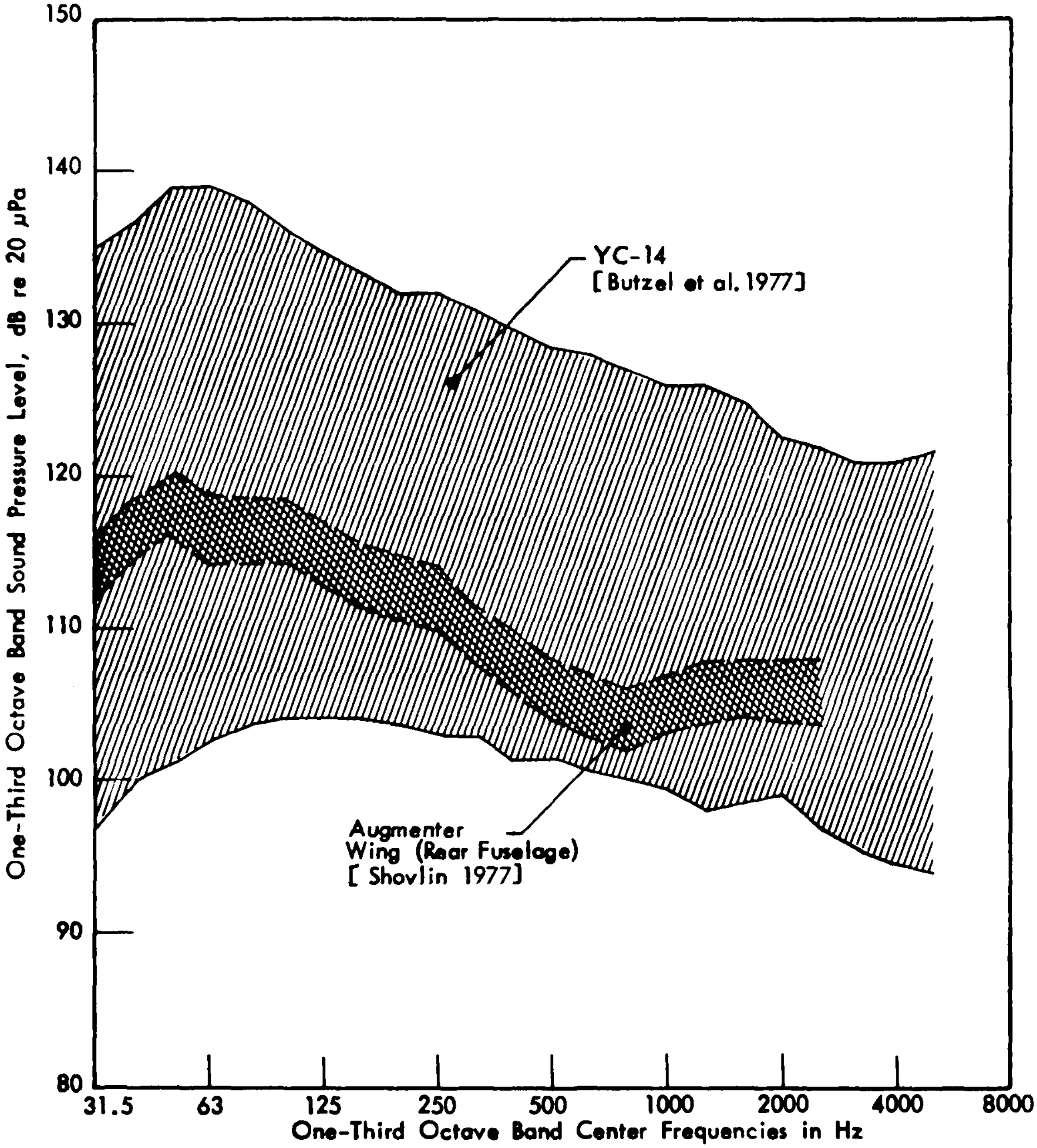

FIGURE A-5. EXTERNAL SOUND PRESSURE LEVEL: DESCENT SCALED TO 150,000 lb T/O WEIGHT AIRPLANE

are 5 to 15 dB lower than those at takeoff. However, the noise reduction will be less than that for CTOL airplanes because the noise generation mechanisms for jet powered-lift systems are less sensitive to airplane forward motion than are jet noise mechanisms (Falarski et al., 1975; 1976). Spectrum levels predicted for the four-engined USB airplane are also shown in Figure A-3 and they are seen to lie in the lower range of values for the two-engined design. There are two reasons for these lower levels. First, the four-engined airplane has smaller engines and the acoustic frequency is shifted to higher frequencies and, secondly, the noise generation mechanisms move further outboard along the wing, away from the fuselage.

Cruise pressure levels are shown in Figure A-4, and in this case values for the STOL designs are not much different from those for CTOL aircraft of similar size. This is to be expected because all STOL powered-lift systems will be retracted at cruise in order to minimize airplane drag, and the STOL airplanes will have CTOL airplane characteristics. Differences between fuselage sound levels for STOL and CTOL airplanes in cruise will be due mainly to differences in engine spanwise location -- the nearer the engine is to the fuselage, the higher will be the sound pressures on the fuselage. Since STOL aircraft tend to have engines mounted close to the fuselage to minimize engine-out control problems, the sound pressures on the fuselage will be somewhat higher in cruise than for CTOL aircraft.

Figure A-5 shows the range of values of exterior sound levels measured on the YC-14 airplane fuselage for several STOL

configurations associated with final descent and approach. The lower end of the range is associated with locations on the forward part of the fuselage, and the range is wide because of the large variation in sound level with STOL configuration. However since the location of maximum sound level changes with STOL configuration, the range of interior noise levels, which effectively represents an integrated effect of the exterior levels, will be less than that for the exterior.

A(b). *Interior Noise Levels*

The exterior pressure levels in Figures A-2 through A-5 can now be used as a basis for predicting interior noise levels. To be consistent with the data for CTOL aircraft in this report, interior noise levels for STOL aircraft are determined in terms of space-averaged spectra. This is accomplished by first reducing the data in Figures A-2 through A-5 to a set of four mean exterior pressure spectra, one for each flight condition, and then adjusting the spectra to account for noise reduction characteristics of the fuselage structure and treatment. The four mean spectra are plotted in Figure A-6 in terms of octave band levels.

Typical noise reduction characteristics for the fuselage sidewall have been estimated using a combination of analytical and empirical results. Two conditions have been considered, one being associated with takeoff, initial climb, and final descent, when the fuselage is essentially unpressurized and the propulsive system is the dominant noise source. The other is associated with cruise when the fuselage is pressurized and the turbulent boundary layer is the main noise source. Data for the unpressurized case are shown in Figure A-7. Test data from the YC-14 and from CTOL commercial aircraft show similar noise reduction values at low frequencies but the CTOL data show the higher noise reductions at high frequencies.

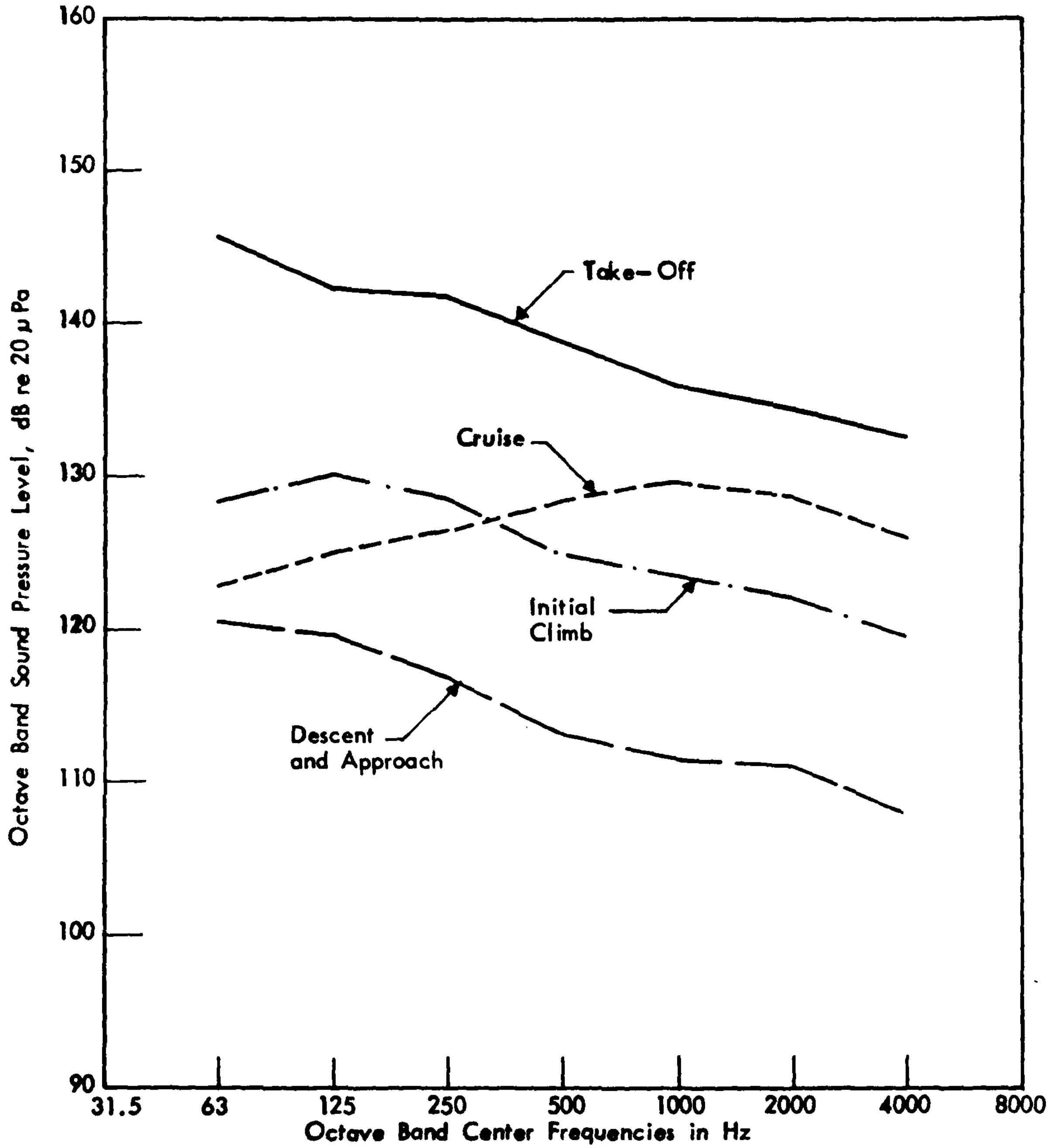

FIGURE A-6. ESTIMATED SPACE-AVERAGED EXTERIOR PRESSURE SPECTRA FOR STOL AIRCRAFT

This difference at high frequencies is due to the YC-14 having only partial noise control treatment. The CTOL data are consistent with analytical predictions as is shown in (Wilby et al., 1974). Thus the CTOL data have been used as a basis for the present noise reduction model for STOL aircraft. The term "standard" interiors is used to identify fuselage structure and sidewall treatments which are similar to those in current turbofan-powered CTOL aircraft. These structures are assumed to be of conventional aluminim skin-stringer-frame construction, while the treatment consists of a layer of glass-fiber wool, with a density of about 9.6 kg/m^3 (0.6 lb/ft^3) and a thickness of 10 to 13 cm (4 to 5 inches), covered by cabin trim panels with a surface weight of about 1.7 kg/m^2 (0.36 lb/ft^2). The cabin is assumed to be furnished with carpets and seats.

In addition to the standard treatment, it is assumed that additional noise reduction can be achieved by use of an "improved" treatment which is based on analytical studies for high-speed propeller-driven aircraft (Rennison et al., 1979; Revell et al., 1980). The additional noise reduction is achieved mainly by use of heavy-weight limp trim panels. The estimated noise reduction achievable by the improved treatment in an unpressurized cabin is shown in Figure A-7.

Estimated and measured noise reductions for cruise conditions are higher than those for pressurized cases as can be seen by comparing data in Figures A-7 and A-8. There are several reasons for this difference, the two main factors being that (1) the subsonic turbulent boundary layer is less effective at exciting the fuselage structure than are acoustic waves, and (2) the cabin pressure differential changes the structural response. Average noise reduction spectra for the standard

and improved interiors were determined in the same manner as for an unpressurized fuselage, and the resulting spectra are shown in Figure A-5. When the spectra in Figures A-6 through A-8 are combined, two sets of space-averaged interior noise spectra can be constructed for typical jet powered STOL aircraft. These spectra are shown in Figure 17 and 18 of the main body of this report (reproduced here as Figures A-9 and A-10) for standard and improved sidewall treatments respectively.

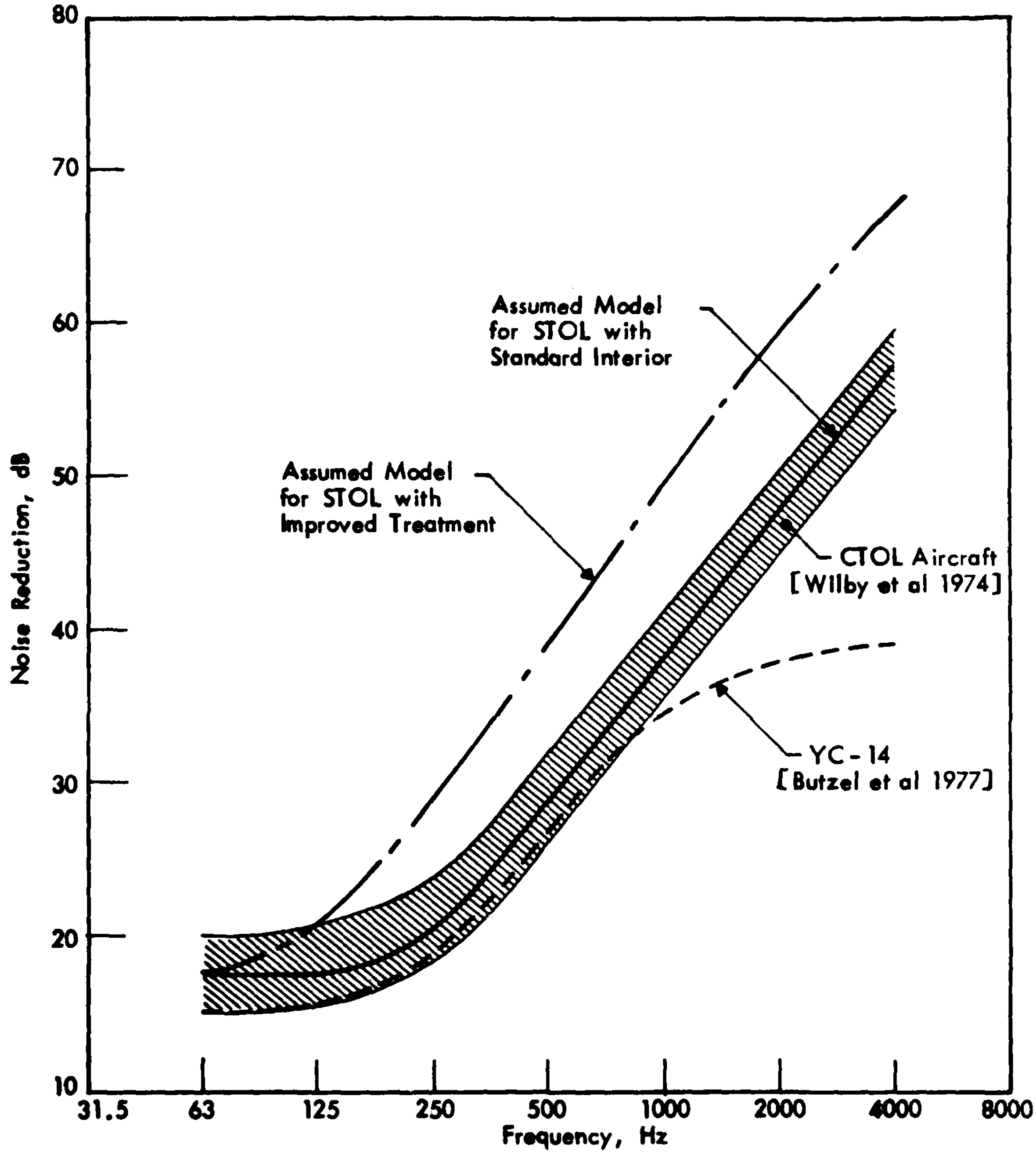

FIGURE A-7. NOISE REDUCTION PROVIDED BY FUSELAGE STRUCTURE AND SIDEWALL TREATMENT (TAKE-OFF, CLIMB AND DESCENT)

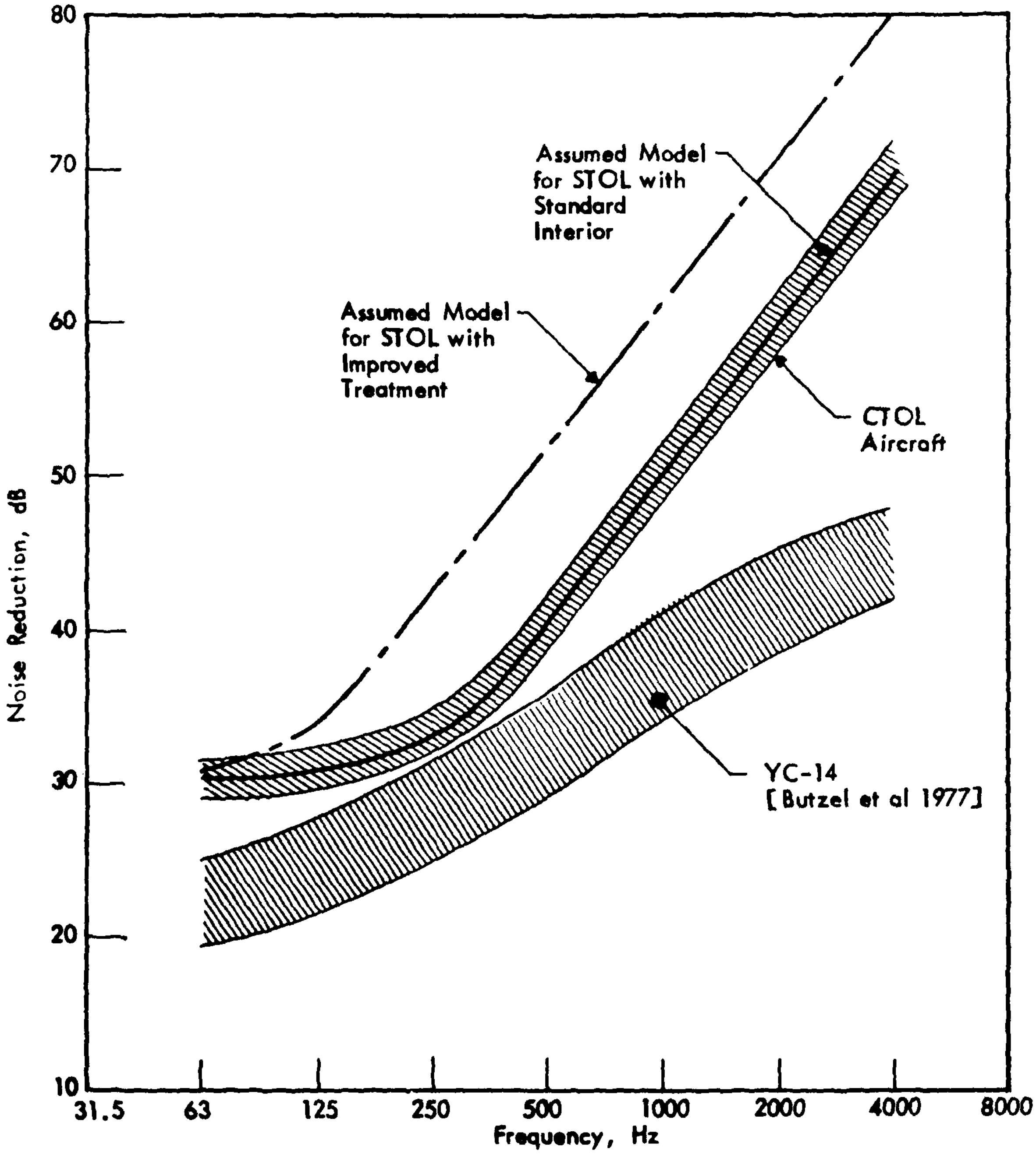

FIGURE A-8. NOISE REDUCTION PROVIDED BY FUSELAGE STRUCTURE AND SIDEWALL TREATMENT (CRUISE)

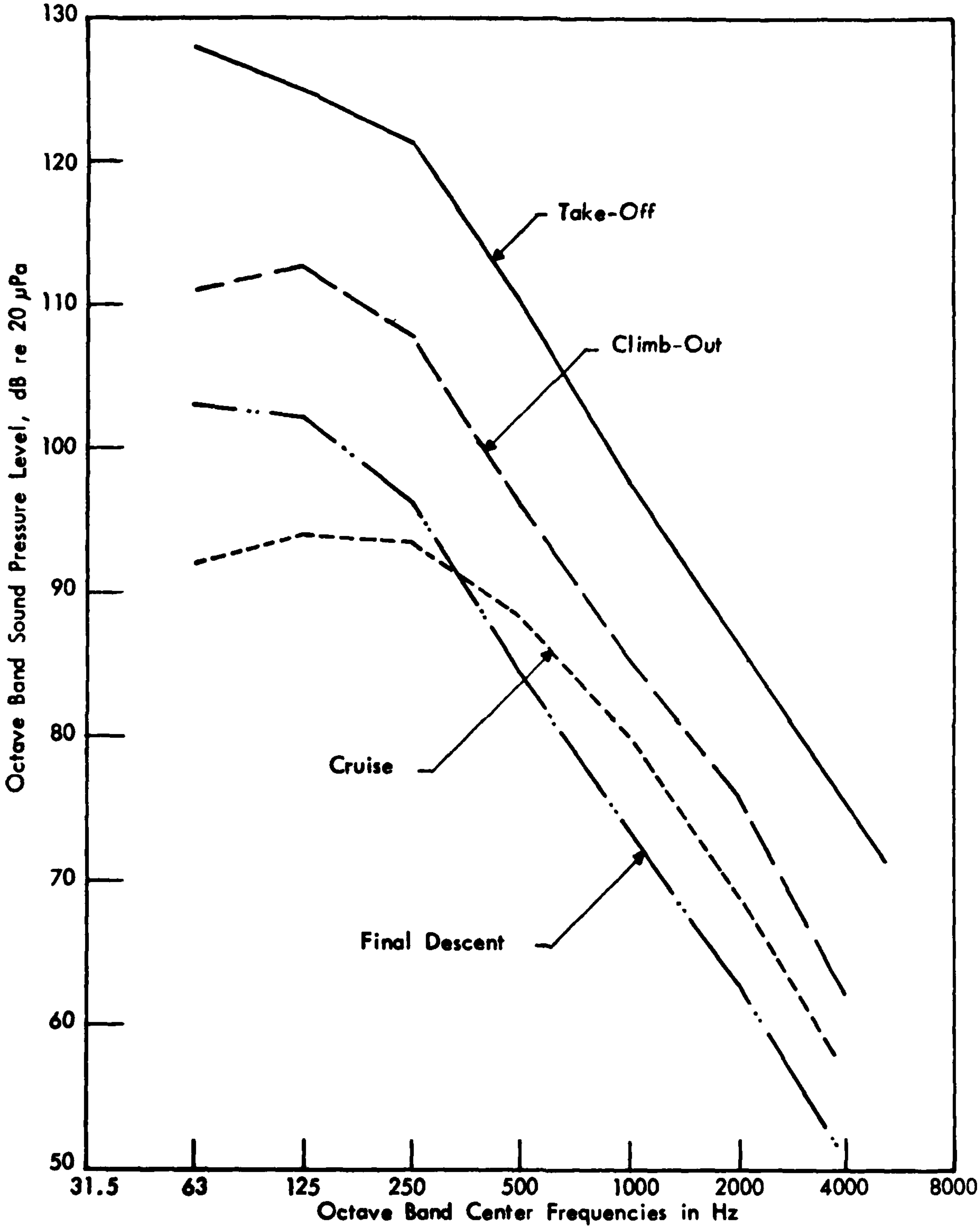

FIGURE A-9. PREDICTED AVERAGE CABIN INTERIOR NOISE LEVELS FOR JET-POWERED STOL AIRCRAFT (STANDARD INTERIOR)

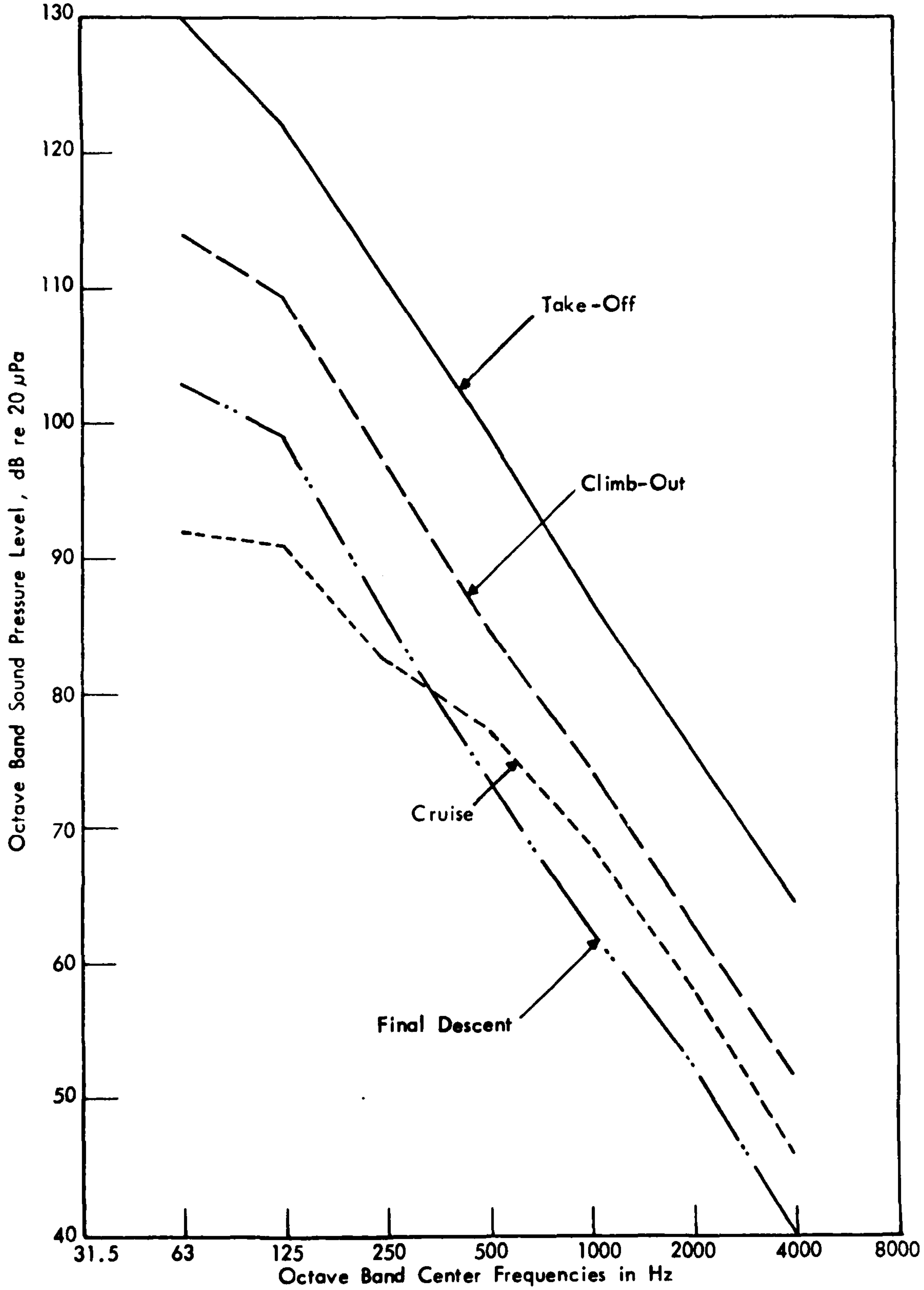

FIGURE A-10. PREDICTED AVERAGE CABIN INTERIOR NOISE LEVELS FOR JET-POWERED STOL AIRCRAFT (IMPROVED INTERIOR)

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